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Distinctions Between Reefs and Bioherms Based on Studies of Fossil Algae: Mizzia, Permian Capitan Reef Complex (Guadalupe Mountains, Texas and New Mexico) and Eugonophyllum, Pennsylvanian Holder Formation (Sacramento Mountains, New Mexico).

Brenda Kirkland George
Louisiana State University and Agricultural & Mechanical College

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George, Brenda Kirkland, Ph.D.

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300 N. Zeeb Rd.
Ann Arbor, MI 48106

DISTINCTIONS BETWEEN REEFS AND BIOHERMS BASED ON STUDIES OF FOSSIL ALGAE: *MIZZIA*, PERMIAN CAPITAN REEF COMPLEX (GUADALUPE MOUNTAINS, TEXAS AND NEW MEXICO) AND *EUGONOPHYLLUM*, PENNSYLVANIAN HOLDER FORMATION (SACRAMENTO MOUNTAINS, NEW MEXICO)

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Brenda Kirkland George
B.A., The University of Texas, 1980
B.S., The University of Texas, 1982
M.S., Texas A&M University, 1986
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Dedicated to Mom and Dad, Peter, and Olaf.

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ABSTRACT

The udoteacean alga *Eugonophyllum* is well-preserved in the Virgilian Holder Formation, Sacramento Mountains. Original aragonite occurs as a felt-like mesh of needles in algal thalli, mollusc fragments, sponge walls, botryoidal, and isopachous marine cements. In the basal, heavily calcified portion of *Eugonophyllum* the interior region of the thallus is composed of aragonitic felt punctuated by 20 μm diameter, parallel siphons. In the distal, less calcified portion of the thallus, irregularly arranged siphons are larger. This study substantiates suggested similarities between Pennsylvanian/Permian phylloid algal mounds and Holocene *Halimeda* mounds.

The Permian dasyclad *Mizzia* is important for paleoecological study in the Guadalupe Mountains, because it has a modern, morphologically similar analog – *Cymopolia*. *Mizzia* dominates grainstone, packstone, and wackestone shelfward of the Capitan reef. Infrequent broken segments (average 10%) and discovery of intact and branched sections of thallus suggest that wave energy did not limit diversity. Instead, an arid climate and the euryhaline tendency of modern dasycladacean algae suggest that hypersalinity limited diversity. This conclusion is incompatible with the widely accepted marginal mound hypothesis for deposition of the reef complex, but is compatible with a barrier reef model.

The Capitan Formation of the Guadalupe Mountains is dominated by a diverse assemblage of calcareous sponges that acted as framebuilders and encrusting organisms that acted as binders. Reef framework contains internal sediment and marine cement. All aspects of Capitan lithology are analogous to modern reef lithology. Relict spur and groove structures are

preserved along the escarpment between Walnut and Rattlesnake canyons. *In situ* reef framework occurs on spurs, while carbonate sands with small (10 cm) bedforms occur in grooves. Diverse reef boundstone is abruptly transitional shelfward to bioclastic packstone and grainstone. The latter lithofacies probably represents a backreef apron deposit. Shelfward, peloid packstones and dasyclad foraminifera packstones were probably deposited in a hypersaline, backreef lagoon. Further shelfward stromatolites, dasycladacean algae, foraminifera, and ostracods accumulated in a muddy, subaerially exposed tidal flat. Shelfward of the tidal flat, tepee structures and pisoids were associated with seeps driven by the difference in water surface elevation between the outer shelf lagoon and the interior, evaporitic lagoon.

CHAPTER I

INTRODUCTION

This dissertation began as a series of studies on carbonate rocks containing fossil algae. It evolved into an exercise in application of the definition of the terms "reef" and "bioherm," and it resulted in improvements of our understanding of each of these depositional systems. The study areas are among the most important localities in the United States for teaching students and professionals about carbonate depositional systems.

The two study areas are in southern New Mexico. The first, the Sacramento Mountains and Tularosa Basin of south-central New Mexico, has impressive exposures of Precambrian and Ordovician through Permian rocks. Particularly noteworthy is the repeated occurrence of bioherms in Mississippian, Pennsylvanian, and Permian strata. A bioherm is a mound-like mass of rock enclosed by rock of different lithology (Gary et al., 1972). The bioherms in the Pennsylvanian and Permian of the Sacramento Mountains are dominated by calcareous algae. These bioherms, largely because of their similarity to subsurface reservoirs, have been described in great detail by many workers.

The first study documents the discovery of well-preserved, aragonitic phylloid algae from a thin (20 cm) bed in the Pennsylvanian Holder Formation. Prior to this discovery, the nature and affinities of phylloid algae in these, and other, Pennsylvanian bioherms were in question. Taxonomic classification of these fossils provides key evidence linking these ancient phylloid algal mounds with their recently discovered modern analog, *Halimeda* bioherms.

The second and third studies concern the Guadalupe Mountains of southeastern New Mexico. This area provides exposures of a Permian

anywhere in the world. The shelf margin carbonate complex of the Guadalupe Mountains has also been the focus of repeated investigations, and is an area of much interest to petroleum explorationists. The formations exposed in the Guadalupe Mountains, and associated with the Capitan reef complex, form productive hydrocarbon reservoirs in the subsurface of the Permian basin approximately 100 km (62 mi) to the west.

The first of the two Guadalupe Mountain studies is a comparison of the Permian dasycladacean alga, *Mizzia,* to an extant dasyclad with analogous morphology, *Cymopolia.* This study suggests that *Mizzia* thrived in restricted, possibly hypersaline conditions. This interpretation, when considered along with the distribution of *Mizzia,* is incompatible with the widely accepted marginal mound model (Achauer, 1968). This model places reef growth below wave base and predicts open ocean circulation on the outer shelf. A barrier reef model of deposition, however, does allow for formation of hypersaline conditions on the outer shelf.

The barrier reef model, initially proposed between the years 1929-1960 (Lloyd, 1929; Johnson, 1942; Adams and Freznell, 1950; Newell, 1952; Adams and Rhodes, 1960), was essentially abandoned in the 1960's and 1970's in favor of the marginal mound model. With few exceptions (Cys, 1970; Cronoble, 1974), the marginal mound model has rarely been questioned. The *Mizzia* study highlighted the need for a second, broader based study of the Capitan reef-complex.

This second study, which builds upon the first, presents observations that support a barrier-reef model for deposition of the Capitan and associated formations. The observations and interpretations that support the barrier reef model include: framework, binders, internal sediment, and abundant marine cement in the Capitan Formation; a back reef lagoon

(outer shelf) containing a biotic assemblage indicative of restricted, hypersaline conditions; and a subaerially exposed, low-energy tidal flat island, also on the outer shelf.

Both study areas, the bioherms of the Sacramento Mountains and the Capitan reef of the Guadalupe Mountains, have been visited over the years by many workers, and during the 1950's and 1960's were the sites of fundamental research supporting the development of a branch of geology known as "carbonate sedimentology." Early study of these two areas proved the need for thorough, precise definitions of the terms "reef" and "bioherm" (Dunham, 1970; Heckel, 1974).

Early studies of the area suggested that the same depositional model was acceptable for these two areas (Wilson, 1977; Tucker and Wright, 1990). The Capitan complex and phylloid algal bioherms were considered to be similar to each other. Both types of buildups were described as "foreslope mud-mounds with sand shoals and islands upslope" (Tucker and Wright, 1990) , and both types of build ups were considered to have no modern analog. The papers that follow show that this model can now be revised. The Capitan complex and the bioherms of the Sacramento Mountains are examples of fundamentally different depositional systems, and generalized models for each of these separate and distinct systems are in reality very different from the currently accepted classification.

Knowledge of the depositional system in each area is directly applicable to hydrocarbon exploration. A better model for deposition of the Capitan complex may lead to improved understanding of the geometries of associated productive formations. This model may also be applicable to other reef systems. Clear evidence about the affinities of phylloid algal fossils from the Sacramento Mountains, when combined with the recent

discovery of modern *Halimeda* bioherms, will lead to an improved depositional model for ancient phylloid algal bioherms, and will probably lead to models designed to predict reservoir geometry and porosity distribution.

These basic improvements in the understanding of two significant ancient depositional systems came about primarily through study of two species of fossil calcareous algae.

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CHAPTER II

Remarkably Well Preserved, Aragonitic Phylloid Algae (*Eugonophyllum*, Udoteaceae) from the Pennsylvanian Holder Formation, Sacramento Mountains, New Mexico: The Missing Link

INTRODUCTION

Abundant and remarkably pristine aragonite is preserved as a felt-like mesh of microcrystalline needles in algal skeletons, as larger crystals in mollusc shell fragments, as spherulites in sponge walls, and as elongate needles in botryoidal and isopachous marine cement. These aragonitic allochems and cements occur in the Virgilian Holder Formation in a 20-cm-thick bed of phylloid algal packstone.

Aragonite is metastable at standard temperature and pressure and is generally soluble in meteoric water. Aragonite is rare in pre-Pleistocene rocks, and it is even rarer in Paleozoic rocks. Examples of Paleozoic aragonite include fossil mollusc shells and sponge spicules (Brand, 1981; Burchart and Weiner, 1981; Veizer and Wendt, 1976; Hallam and O'Hara, 1962; Stehli, 1956) and microscopic, relict aragonite in replacement cements (Sandberg, 1985).

The discovery of virtually pristine Paleozoic primary aragonite and calcite in the Sacramento Mountains provides an excellent resource for geochemical studies (Dickson *et al.*, 1991). In addition, preservation of a felted mesh of pristine aragonite needles in *Eugonophyllum* is previously unknown. The preservation of these algae, their taxonomic affinities, and the implications of this discovery to understanding of algal bioherms are the focus of this paper.

METHODS

Samples were collected with attention to orientation and to position in the bed. Description of color in hand sample uses terminology from the Geological Society of America rock color chart (Goddard *et al.*, 1948). X-ray diffraction was used to confirm the presence of aragonite and to determine the composition of the associated shales. Thin sections were studied using a petrographic microscope and cathode luminescence (CL) (Technosyn 8200MkII). Before coating with gold for study with scanning electron microscopy (SEM), polished surfaces of sponges (0.05 alumina grit) were etched with 0.25% formic acid for 90 seconds (after Sandberg, 1985) and polished surfaces of algae were etched with dilute HCl for 10 seconds. Sr levels were determined using a Jeol 733 Super Microprobe (beam current: 29.8 na, beam size: 1μm, accelerating voltage: 15 kv, approximate minimum detection limits for Sr: 100 ppm, system error: < 1%).

GEOLOGIC SETTING

The small packstone bed containing aragonite is in Dry Canyon, three miles northwest of the city of Alamogordo in Otero County, New Mexico. The bed is within the Holder Formation (Fig. 1.1) stratigraphically above the basal bioherm complexes, and is either stratigraphically just below or within the initial phase of cyclic depositional sequences containing small carbonate bioherms, shale, sandstone and conglomerate (Pray, 1961). The exposure is only 120 cm long, and has been eroded on the eastern side by a

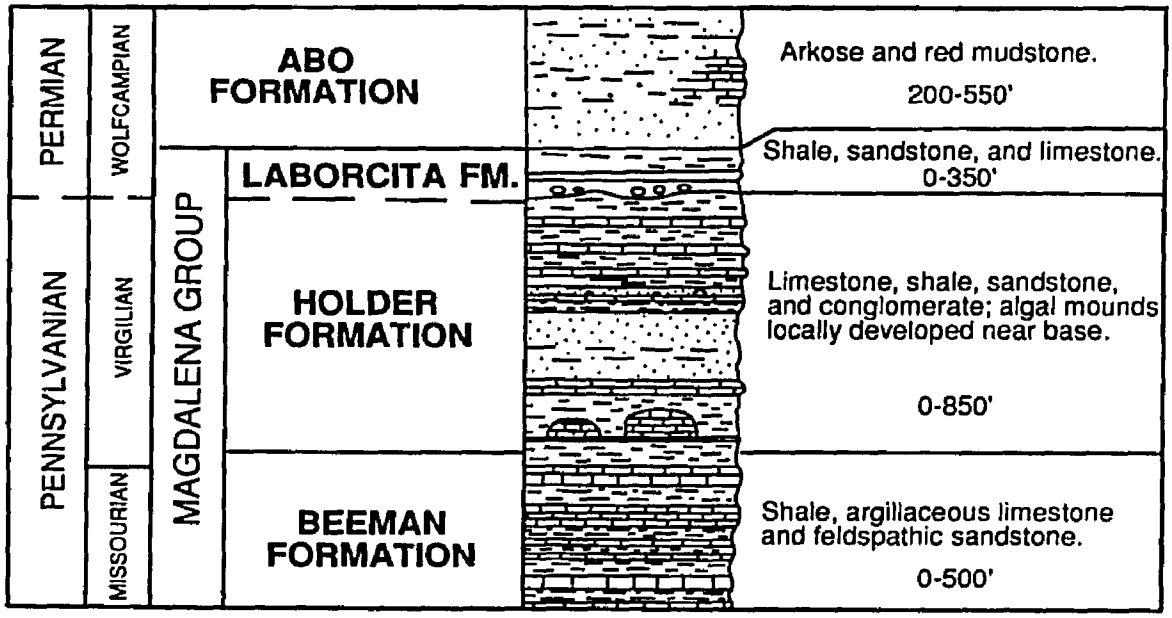

Figure 1.1. Stratigraphic column showing position of Holder and Laborcita formations (modified from Toomey and Babcock, 1983).

paleochannel and on the western and southern side by Holocene processes. The packstone is 20 cm thick and is interstratified between two thick shale beds. The shale below the packstone is at least 1.6 m thick and the shale above the packstone is 8 m thick. No other aragonite bearing-beds were found in equivalent or in associated horizons. None of the fossils appear to be in life position and most of the phylloid algal segments are oriented with their long dimension parallel to the bedding plane. The packstone has no visible porosity in hand sample, under the petrographic microscope, or with SEM. The shales are yellowish gray, dominated by mixed-layer clays, contain 0.21 (upper) and 0.22 (lower) total organic carbon. These shales show no obvious porosity with SEM, and probably sealed and isolated the layer of aragonite-bearing packstone.

PETROLOGY

In outcrop and associated float, the outer, weathered surface of the packstone is covered with powdery grayish orange to dark yellowish orange dust. Fresh surfaces contain very light gray to very pale orange fossils set in a dark gray matrix. Fossils visible in hand sample include sponges (0.05 cm) and large (1 cm) crinoid ossicles. Phylloid algae dominate. Segments of the latter are $\leq$1 mm thick and range from 1-40 mm long. In hand sample, they appear morphologically identical to the phylloid algae that dominate the core facies of the Yucca mound complex, as well as the large bioherms exposed in Dry Canyon and at Scorpion mound.

In thin section, preservation of the phylloid algae is striking.

Unlike most examples of phylloid algae, in which internal structure is dissolved and replaced, these samples exhibit internal microstructure consisting of a homogeneous brown felt similar to that of modern *Halimeda* (Fig. 1.2, 1.3). Observation with SEM reveals that this felt contains square-tipped aragonite needles (10 μm long) (Fig. 1.4). The presence of aragonite in these algal thalli is also confirmed by X-ray analysis (Dickson *et al.*, 1991 in press). Under cathode luminescence, the felted fabric is gray-green. Microprobe analysis of felted zones shows Sr levels of 9191 ppm (n=21, standard deviation = 1498), consistent with Sr levels in modern *Halimeda* (average 8957.5 ppm) (Kinsman, 1969). Mg levels in these ancient samples were generally below detection limits.

In thin section the preservation of sponges is also striking. In some, fascicular (or spherulitic) microstructure (Majewsky, 1969) is preserved. Internal areas are partitioned by irregular walls into two relatively larger internal cavities and numerous smaller, irregular outer cavities. These sponge walls are dully luminescent under CL and have Sr levels of 5049 ppm (n= 24, standard deviation = 1736). These specimens are among the oldest known preserved calcareous sponges (Wood, *et al.*, in preparation).

Other fossils in this bed are sparse. They include: fusulinids, encrusting foraminifera, ostracods, brachiopods, bryozoans, molluscs, and trilobite fragments.

A variety of cements and authigenic minerals are also present in the packstone. Early marine cements include botryoidal aragonite occurring as fans and crusts (from 0.1 - 10.1 mm thick), usually on

Figure 1.2. Photomicrograph. Interior structure of well preserved *Eugonophyllum* from aragonite-bearing packstone bed in the Holder Formation. Homogeneous felt is punctuated by randomly arranged, small, microspar-filled circles, which are more abundant in the cortical region.

Figure 1.3. Photomicrograph. *Eugonophyllum* thallus with cortical quartz rind. Oval structures are visible within the rind on the lower margin of the thallus. Origin of the two dark lines within the thallus is unknown; they are unique to this specimen.

Figure 1.4. Scanning electron photomicrographs A. Aragonitic felt in interior of Pennsylvanian *Eugonophyllum* thallus from Holder Formation packstone. Scale bar 10 μm. B. Inner surface of a utricle in *Halimeda*, Holcene, Java Sea. Scale bar 1 μm.

algal thalli and occasionally on both sides of an algal thallus. Under CL, botryoidal cements are black, except for areas replaced by medium crystalline (100 μm) mosaic calcite spar that may be dully luminescent. The shape of the replacement mosaic spar appears to be vaguely controlled by the shape of the aragonite crystals, and the intercrystalline boundaries of the replacement spar are wavy and interlocking. A second type of early marine cement – an isopachous rim (50-125 μm wide) of pristine, acicular aragonite cement – occurs inside some sponges, gastropods, and foraminifera. The third, and most intriguing, type of aragonitic cement occurs in the interior of some poorly calcified algal thalli. Highly birefringent, prismatic crystals grew into the interior of the algae and some were later encased by large, sometimes poikilotopic, calcite spar. These prismatic crystals are morphologically similar to the individual aragonite crystals of the isopachous rims, but they are larger (average 98 μm long and 13 μm wide). The high concentration of Sr revealed by microprobe elemental mapping suggests that these crystals are aragonite. In a marine setting, Land and Moore (1980) observed similar crystals forming in deep Holocene forereef deposits off Jamaica. They apparently form slowly in marine waters near the aragonite lysocline.

Other diagenetic features include a 50-100 μm wide crust of euhedral quartz crystals surrounding many algal blades. In these crusts, the pyramidal termination of the quartz crystal is always directed toward the interior of the thallus and the opposite end of the crystal ends at the edge of the thallus. In a few specimens these crusts are partially calcite. These replacement crusts obliterate the

aragonitic felt, but in some specimens large (average 40 by 59 μm), micrite-filled, oval-shaped structures of the algae are still visible. Also associated with the quartz crusts are fibrous, needle-like crystals. These crystals are usually completely encased in quartz and, like the quartz, the sharp needle-like termination is directed toward the interior of the thallus. The opposite end of the crystal almost always terminates at the edge of the thallus. These tiny crystals are probably some form of carbonate. The quartz crusts are common, but not ubiquitous. Where the blades are well preserved and have no thick quartz crust, a thin (16 μm) layer of calcite or chalcedony occurs along the margin (Fig. 1.2).

Other authigenic components include pyrite, small areas of kaolinite, possible magnetite, tiny chlorite crystals, hematite, sparry calcite mosaic, and inclusion-rich calcite spar with undulose extinction.

DESCRIPTION OF THE ALGA

The original description of the alga *Eugonophyllum johnsonii* Konishi and Wray (1961) was made on samples in which the inner medullary zone was recrystallized. Despite poor preservation of the specimens, their description is remarkably accurate, and they were able to describe most major features of the algae. In addition to this initial description, Cross and Klosterman (1981) provided a reconstruction of the gross external morphology of a phylloid alga based on serial slabbing and field observations of completely recrystallized algal thalli. Study of some of their samples, deposited in the Louisiana State University (LSU) Teaching Collection,

confirmed their tentative identification of the reconstructed alga as *Eugonophyllum.* The description given in our paper augments the original description of Konishi and Wray and links major features of the algae, as seen in thin section, to the reconstruction by Cross and Klosterman.

Cortex of thallus

On the upper surface of some hand samples, natural weathering processes have delicately etched fossil algal surfaces and have revealed astounding detail (Fig. 1.5A). Cell structure is preserved on the outer surface of some algal plates. The cells are polygonal (0.05 mm diameter) and tightly packed forming the outer surface of the plant. This arrangement is almost identical to the exterior cortex of live *Halimeda* (Fig. 1.5 A, B).

In thin section, cuts tangential to the surface of the algae appear as net-like zones of polygonal cells (Fig. 1.6). The walls of these cells are approximately 10 μm thick and the polygons are approximately 50 μm in diameter. These net structures are usually composed of fibrous chalcedony, but some contain elongate carbonate crystals as well. A tangential section of *Halimeda* in a thin section from the LSU teaching collection shows a similar net-like pattern, but with micritic microstructure. A section, tangential to, but just below the surface of *Eugonophyllum,* reveals large and small micrite-filled circles (Fig. 1.7)

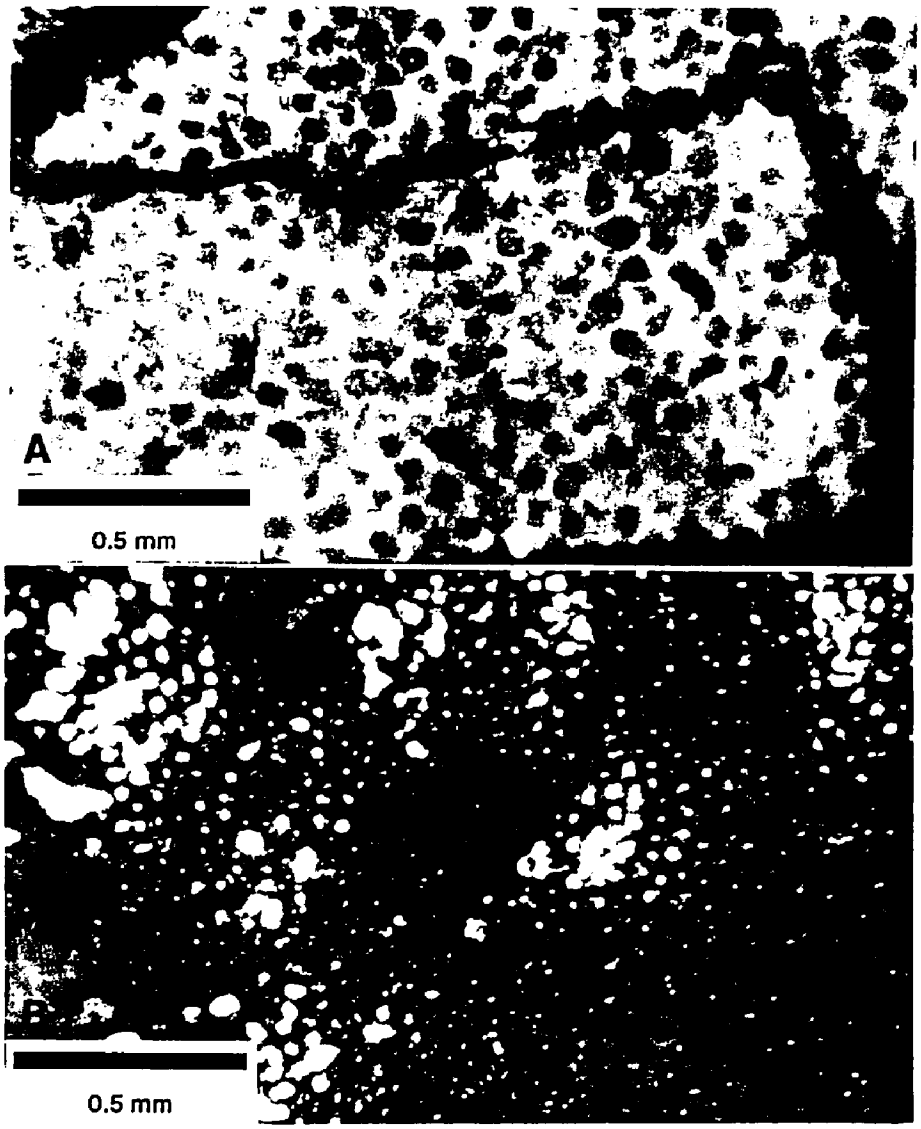

Figure 1.5. Binocular microscope photomicrograph. A. Silicified outer surface of *Eugonophyllum* on weathered float. Probably from the Holder Formation. B. Outer surface of living *Halimeda*.

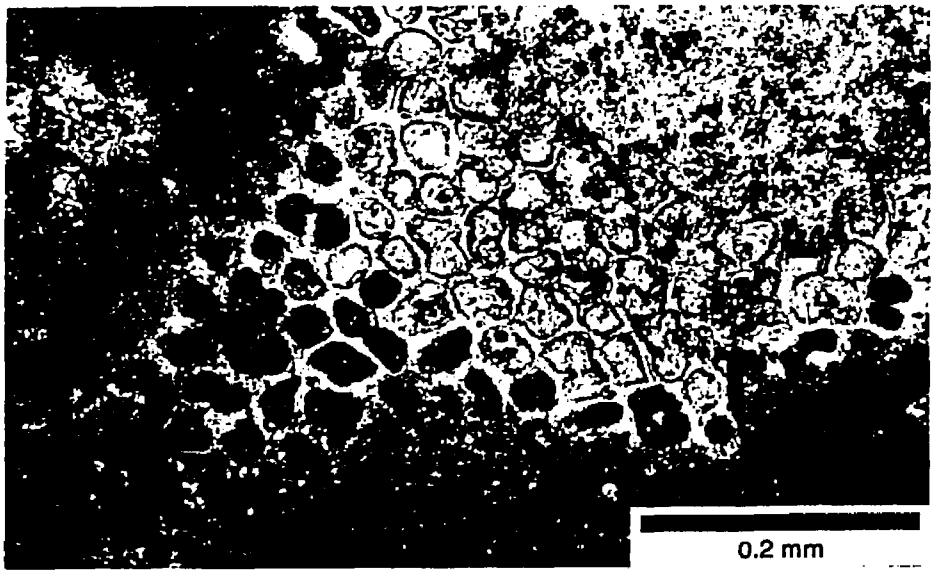

Figure 1.6. Photomicrograph of Holder Formation thin section. Section cut tangential to, and just below, siliceous (chalcedony), outer surface of *Eugonophyllum* thallus revealing net-like pattern.

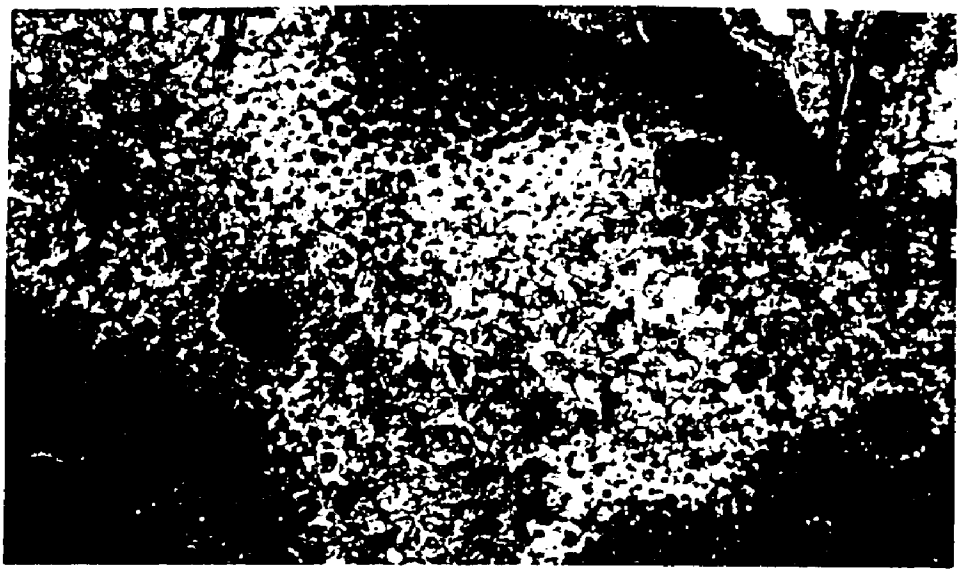

Figure 1.7. Photomicrograph of Holder Formation thin section. Section cut tangential to thallus, but deeper than the section shown in Figure 1.6. Large micire filled circles may be reproductive structures, smaller micrite filled circles may be utricles.

Interior of thallus

The algal thallus fitting the description of *Eugonophyllum johnsonii* Konishi and Wray, 1961 is common in thin section. These algae have heavily calcified thalli, which have an elongate, rectangular shape in outline (Fig. 1.8). In thin section, measured horizontal cross sections through these well-calcified thalli show an average width of 0.45 mm and an average length of 8.72 mm. The interior, or medullary (terminology of Wray, 1977), sections of the thallus are composed of a homogeneous, brown felt of aragonite needles. This felt is punctuated by what appear in thin section to be small (average 15.4 μm), irregularly arranged, microspar-filled "circles" (Figs. 1.2, 1.4, 1.8). Occasionally, usually near the cortex of the plant, these microspar-filled zones are short tubes. Some circles are filled with dark micrite; other circles are filled with what appears in reflected light to be iron oxide (hematite). Near the cortical (exterior) regions of thalli without a quartz crust, the circles are more abundant and may be slightly larger (Fig. 1.2). The subcortex as defined by Konishi and Wray (1961) is a zone that in some segments contains a row of larger (average 40 x 59 μm), oval-shaped structures filled with micrite that is darker than the aragonitic felt of the thallus (Fig. 1.3). Two examples of similar oval-shaped structures were found along the margin of modern *Halimeda* thalli.

Some well-calcified thallus sections composed of a dense homogeneous felt form crescents (1 mm in diameter) or almost closed circles (Fig. 1.9). These sections show spar filled circles (25 μm), and some contain a second smaller inner circle of micrite giving them the appearance of a bright ring of calcite.

Figure 1.8. Photomicrograph. *Eugonophyllum* from Holder Formation packstone bed. Note randomly arranced, small dark circles in the interior of the thalli and larger, circular to oval shaped structures (reproductive structures?) in the cortical regions of two thalli. The white rinds along the margins of, and white zones within, thalli are largely quartz with some calcite.

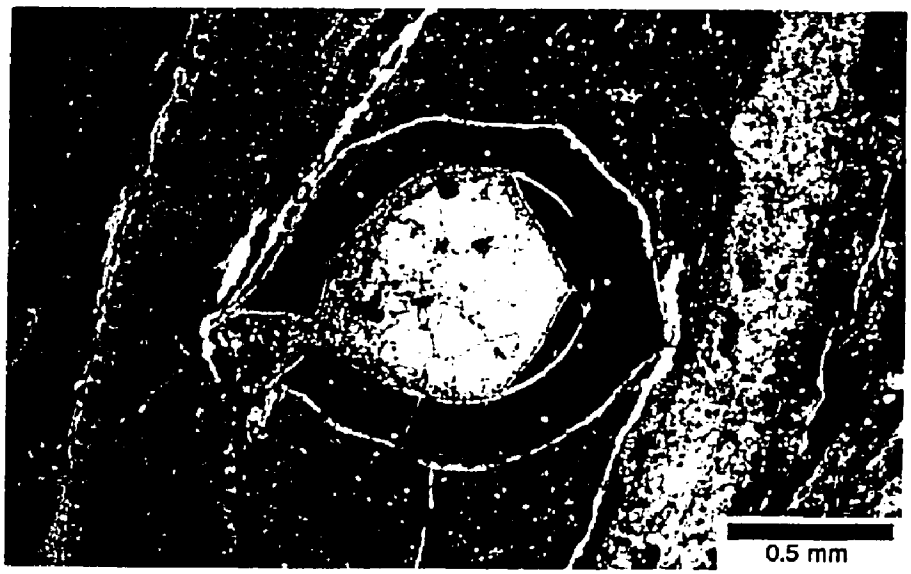

Figure 1.9 Photomicrograph. Thin section from Holder Formation packstone bed. This heavily calcified thallus may be juvenile *Eugonophyllum* or a section near the base of the mature plant.

Some of these thallus sections have an appearance reminiscent of a cross section through a rose bud. These rosette-like sections contain smaller, half-circle-shaped, calcified areas abutting the interior wall of the thallus. In some samples these half-circle-shaped areas are slightly less calcified and none contain spar-filled circles.

In the cortical region of some well-calcified *Eugonophyllum* thalli sections, large (200 μm), circular to oval-shaped structures are visible. These structures are surrounded by a rim of sparry calcite, quartz, and/or chalcedony. The crystals in these thin rims are generally elongate and tangentially arranged. These oval-shaped structures are filled with sparry mosaic calcite, botryoidal aragonite, or rarely with micrite. These structures appear to have a single aperture and are entirely to partially contained within the algal thallus (0-25% of the structure extends above the cortex) (Fig. 1.8).

Sections of less calcified thalli have a much different appearance and do not fit the description of *Eugonophyllum johnsonii*. Tangential cuts through the outermost cortex of these less calcified thalli, however, are similar to tangential cuts through the heavily calcified portions of the plant, suggesting that these are sections through different parts of the same plant. Unlike the regular, rectangular outlines of the heavily calcified thallus sections, these less calcified portions have irregular shapes in outline. Many of these poorly calcified thallus sections exhibit internal structures suggesting tubes. These tubes (?) range from 25-45 μm in diameter, and many have a branched or irregular pattern strikingly similar to modern Udoteaceans (Fig. 1.10). In a few sections, calcification is limited to irregular and randomly arranged strips across the interior

Figure 1.10. Two spliced photomicrographs. Thin section from Holder Formation packstone bed showing large thallus section with irregular shape in outline, less calcification, and possible branching siphons.

of the thallus. Most of these poorly calcified thallus segments contain large (100 x 12 μm) aragonite crystals.

RECONSTRUCTION OF *EUGONOPHYLLUM*

Cross and Klosterman (1981) present a reconstruction of a phylloid alga from Scorpion Mound (Laborcita Formation, Tularosa Basin) that they believed to be *Eugonophyllum*. They based their reconstruction on field observations and serial slabbing of large blocks containing completely recrystallized algal fossils preserved in life position. By comparing our well preserved, but fragmented, fossils to the published reconstruction (Fig. 1.11) and to modern udoteaceans, we were able to combine the internal morphology of our samples with the compete external shape of *Eugonophyllum* and hence produce a complete reconstruction (Fig. 1.12).

Heavily calcified circular thallus sections probably represent sections through basal portions of *Eugonophyllum* or through juvenile plants. The spar filled circles in these sections are probably siphons – elongate tubular cells that parallel the outer walls of the thallus. A similar growth pattern occurs in the juvenile stage of modern udoteacean algae (Bold and Wynne, 1985). The extant alga *Udotea cyanthiformis* has a conical morphology (Littler et al., 1989), which would appear circular in cross section.

Well-calcified thallus fragments, which in section have the external outline of an elongate rectangle, appear to be sections through the middle portion of *Eugonophyllum* (Fig. 1.2, 1.3, 1.8). In this portion of the thallus, there are more microspar-filled circles,

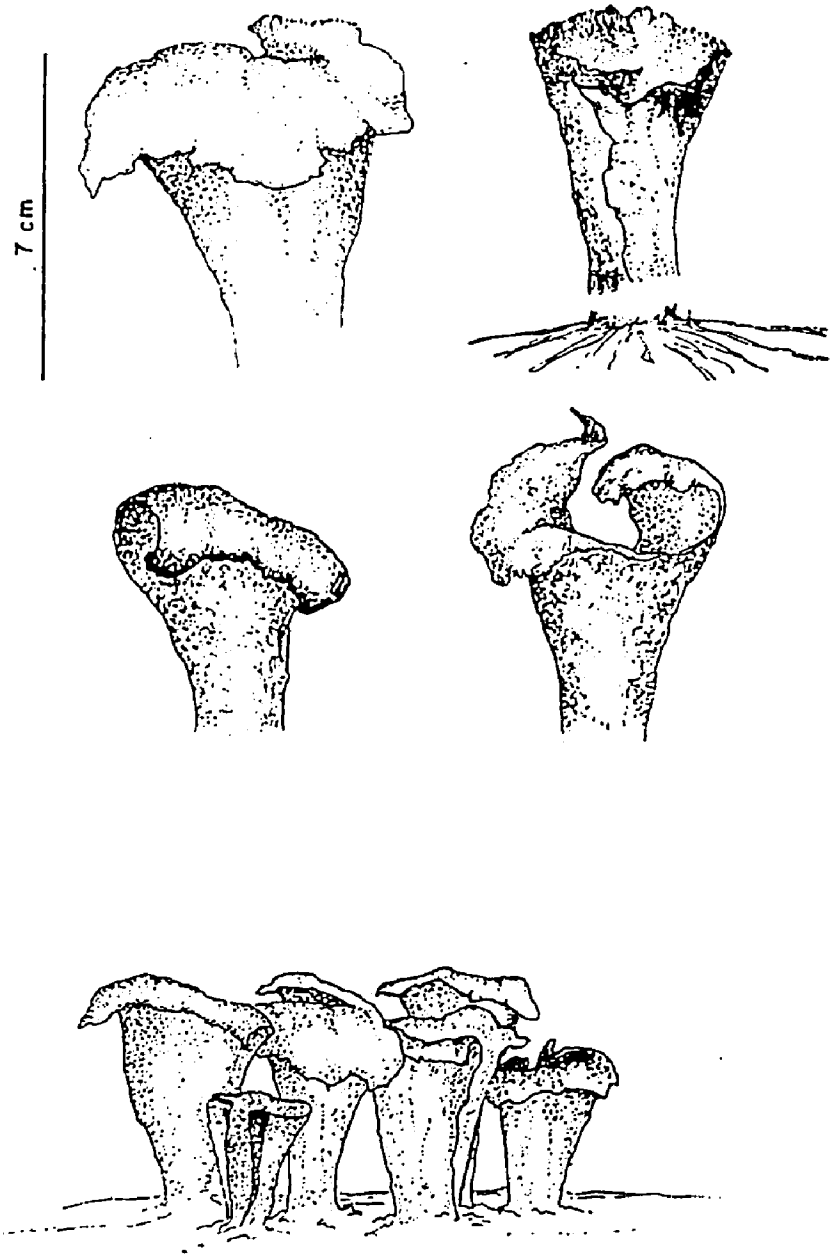

Figure 1.11. Reconstructed exterior morphology of *Eugonophyllum*. Holdfast is conceptual (From Cross and Klosterman, 1981).

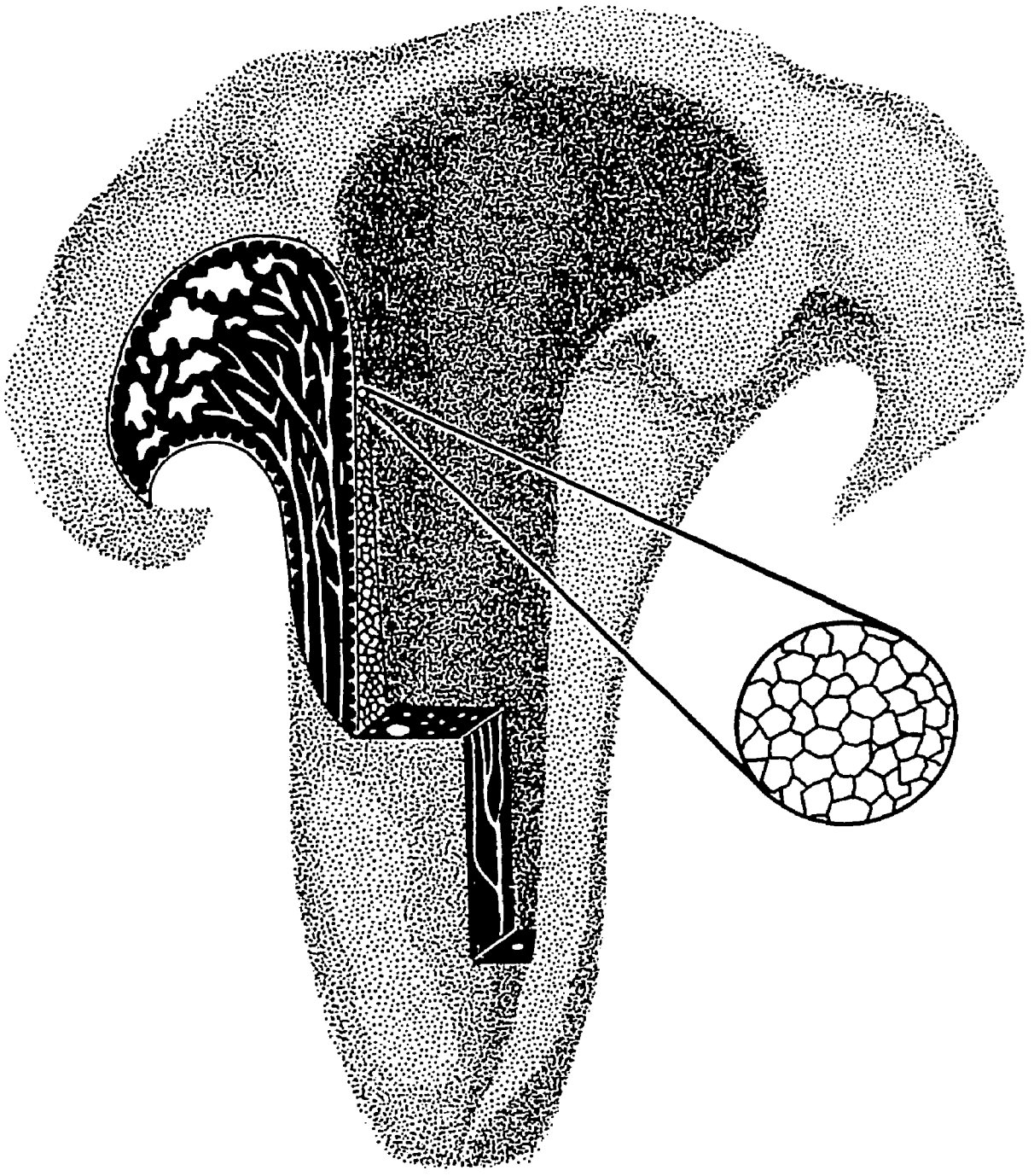

Figure 1.12 Schematic diagram illustrating reconstructed *Eugonophyllum* thallus. External morphology is based on line drawings of Cross and Klostermann (1981).

also interpreted as siphons, than in the basal or juvenile sections (Fig. 1.9). This suggests that the siphons branched as the plant grew upward, analogous to the structure in modern *Penicillus*. The siphons in the basal sections of the plant generally parallel the outer wall of the thallus. This configuration is analogous to the internal structure of modern *Penicillus* or *Udotea* (Bold and Wynne, 1985).

The large, oval structures in the well-calcified portion of the plant were described as reproductive structures by Konishi and Wray (1961) (Figs. 1.8). We agree with their conclusion, but point out, as they did, that this is merely an interpretation.

Along the margin of a few of the well-calcified thallus sections that do not have a silicified crust, more and slightly larger circles are present (Fig. 1.2). These are probably sections through siphons that branch and ultimately swell at the tips. These swollen tips, called utricles, are pressed tightly together forming a pattern of hexagonal cells on the outer-most cortex of some silicified thallus segments. This internal architecture is identical to the structure of modern *Halimeda.*

In the distal, poorly calcified thallus portions, both the external and internal morphologies are irregular. Hence sections through this portion of the algal thallus appear curved or undulose conforming to the reconstruction of Cross and Klosterman (1981). A modern analogy might be a planar cut through somewhat curly lettuce leaves (Figs. 1.10, 1.11).

Cuts through the silicified outer-most cortex of the plant, which show a net-like pattern (Fig. 1.6), provide additional evidence that these variably calcified thallus sections may be parts of the same plant. This

pattern is present and is similar on both heavily and lightly calcified thallus sections. *Eugonophyllum* is often described in association with *Anchicodium* Johnson (1946) The internal structure of *Anchicodium* is similar to the internal structure of the lightly calcified thalli described here, but only two sections were circular and thus could fit Johnson's description of *Anchicodium*. It is possible that some specimens described in the past as being similar to particular species of *Anchicodium* (Johnson,1946) may be parts of the same algal thallus as *Eugonophyllum* (see Figs. 1.7, 1.10).

TAXONOMIC CLASSIFICATION

Konishi and Wray (1961), in their original description of *Eugonophyllum*, placed it in the family Codiaceae. Since their work, classification of these green algae has been updated. The algae, traditionally classified as codiaceans in older geologic texts are now classified under the order Caulerpales. This order is divided into six families including the Codiaceae (containing the modern alga *Codium*) and the Udoteaceae (containing the modern algae *Halimeda, Udotea,* and *Penicillus*). The distinction between the families Codiaceae and Udoteaceae is based largely on features not preserved in the fossil record including: the nature of plastids for storage of food, reproductive processes, and the nature of non-calcified reproductive structures (Bold and Wynne, 1985). Morphological characteristics, however, can be preserved in the fossil record. Based on the similarity of morphological features of *Eugonophyllum* to morphological features of the modern algae *Halimeda* and *Udotea,* we place *Eugonophyllum* in the family Udoteaceae. The only features of *Eugonophyllum* that are not consistent with the family

Udoteaceae are the oval, spar-filled chambers interpreted as reproductive structures (Fig. 1.8). In modern members of the family Udoteaceae, for example *Halimeda* and *Udotea*, gametangia are surficial and non-calcified. In *Codium*, utricles form a compact, pallisade-like outer surface layer. Gametangia are produced from the side of enlarged utricles and within this pallisade-like layer (Bold and Wynne, 1985). While reproductive structures in *Codium* remain within the cortex (Konishi and Wray, 1961), their shape is elongate and differs from the round to oval shape of the structures in *Eugonophyllum*. Perhaps *Eugonophyllum* is an ancestor of both the families Udoteaceae and Codiaceae. Possibly the reproductive structures in *Eugonophyllum* represent a morphological experiment (R.L. Chapman, personal communication). Other possibilites seem less plausible. A number of calcareous (aragonitic) members of the family Dasycladaceae (Order Siphonales) contain circular reproductive structures within their thallus, but the morphology of this group is fundamentally different from that of *Eugonophyllum*. In addition, similarly shaped, though generally larger, conceptacles occur in calcareous (Mg calcite) members of the family Corallinaceae and in calcareous members of the family Pessyonneliaceae/Squamariaceae. Here again, the internal structure and, with the Corallinaceae, the mineralogy of these organisms is fundamentally different from that of *Eugonophyllum*. In summary, preserved internal morphology of *Eugonophyllum* is similar to the modern order Caulerpales (Cholorphyta), and *Eugonophyllum* probably has closest affinities to the modern family Udoteaceae.

SIGNIFICANCE AND IMPLICATIONS

In addition to the formal classification discussed above, *Eugonophyllum* is classified within an informal and artificial group known as the "phylloid algae." Pray and Wray (1963) suggested the form term "phylloid" for leaf-like fossils whose internal structure is completely dissolved or recrystallized. This artificial group is now known to include members of both the divisions (phylum) Rhodophyta and Chlorophyta (James *et al.*, 1988; Moshier and Kirkland, in press). "Phylloid algae" are present, and are even dominant, in many ancient carbonate deposits. For example, *Eugonophyllum* and *Anchicodium* (?) dominate the most abundant facies of Scorpion mound in the Tularosa Basin (Mazzullo and Cys, 1979; Cross and Klosterman, 1981; Wray, 1977).

Confirming *Eugonophyllum's* classification in the Udoteaceae allows us to relate modern udoteacean habitats with the occurrence of fossil Udoteaceae in the rock record. Perhaps most significant among these modern udoteacean-dominated environments are recently discovered *Halimeda* bioherms in the Java Sea, the Nicaraguan Rise, and the northern Great Barrier Reef, Australia (Roberts *et al.*, 1987; Hine *et al.*, 1988, Marshall and Davies, 1988; Roberts *et al.*, 1988). Early studies of these bioherms, dominated by *Halimeda*, suggest that these might be analogous to ancient phylloid algal mounds (Kobluk, 1979; Marshall and Davies, 1988; Brinton, 1990). The discovery of phylloid algae with distinctly udoteacean internal structure provides the key piece of evidence – the missing link – between Late Paleozoic and Modern algal buildups.

Understanding the anatomy and environmental controls on

phylloid algal bioherms has important economic implications. In the subsurface, bioherms dominated by phylloid algae can form tremendous hydrocarbon reservoirs. For example, Horseshoe atoll in West Texas, a complex of phylloid algal bioherms, contains estimated reserves of 2.54 billion barrels of recoverable oil (Vest, 1970). Similar bioherms in the Sacramento Mountains and Four Corners Region have been studied in detail with attention to mound morphology, facies, and patterns of development (Wengerd, 1955; Wray, 1962; Peterson and Ohlen, 1963, Wilson, 1975; Toomey *et al.*, 1977, Mazzullo and Cys, 1979). Perhaps one of the most important pieces of information to be gained from the study of *Halimeda* bioherms is the control over their location - currents of nutrient-rich waters. Perhaps factors such as paleocurrent direction, nutrient-rich water, and water chemistry also controlled the location and trend of phylloid algal mounds. Such information would be valuable to hydrocarbon exploration and each of these possible factors is certainly worthy of further study.

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LOUISIANA STATE UNIVERSITY
AND AGRICULTURAL AND MECHANICAL COLLEGE
Department of Geology and Geophysics

November 27, 1991

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Department of Botany and Plant Pathology
Purdue University
West Layfayette, IN 47907

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CHAPTER III

The Fossil Green Alga *Mizzia* (Dasycladaceae): a Tool for Interpretation of Paleoenvironment in the Upper Permian Capitan Reef Complex, Southeastern New Mexico[1]

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INTRODUCTION

This paper explores the use of *Mizzia* as a paleoenvironmental indicator for the Capitan reef complex and perhaps for other localities. The primary objective is to define the habitat of *Mizzia* by comparing it to its modern analog, *Cymopolia*, by a review of pertinent information including the unique distribution of dasyclads in the Guadalupe Mountains, and by application of lithologic and stratigraphic information from the Guadalupe Mountains and from European localities. The information provided by this one genus of dasyclad algae may be important to interpretation of the entire Permian reef complex.

Calcareous algae first appear in abundance in the geologic record near the Precambrian/Cambrian boundary about 570 million years ago (Palmer 1983, Riding and Voronova 1985) (Fig. 2.1). Few Paleozoic algae resemble modern genera and are often classified as "algae of uncertain affinities" or "alga-like problematica." Reconstruction of paleoenvironment in Paleozoic rocks containing such fossils is difficult. For example, in the Upper Permian (Guadalupian) Capitan Formation of the Guadalupe Mountains of southeastern New Mexico (Fig. 2.2) several examples of "algal problematica" are present (Babcock 1986). Because these organisms have no apparent modern analog, even a well executed and thorough study (Babcock 1974) may not provide an adequate basis for paleoenvironmental interpretation.

In addition to problematic algae, a variety of sponges contribute to the framework of the Capitan reef. A better understanding of these sponges will certainly improve our understanding of this

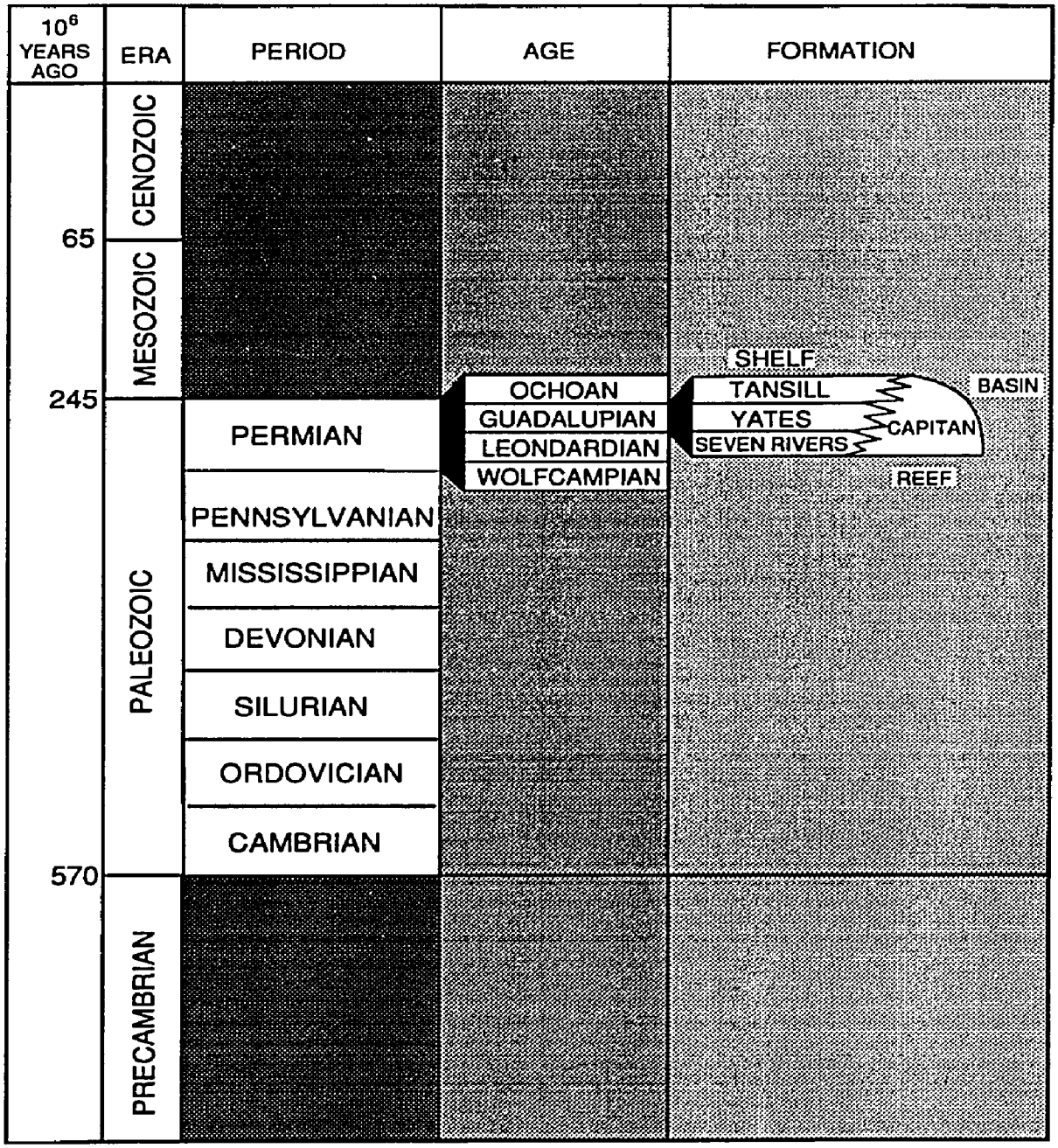


Fig. 2.1. Geologic time scale showing relative age of the formations studied. Modifed from Palmer (1983).

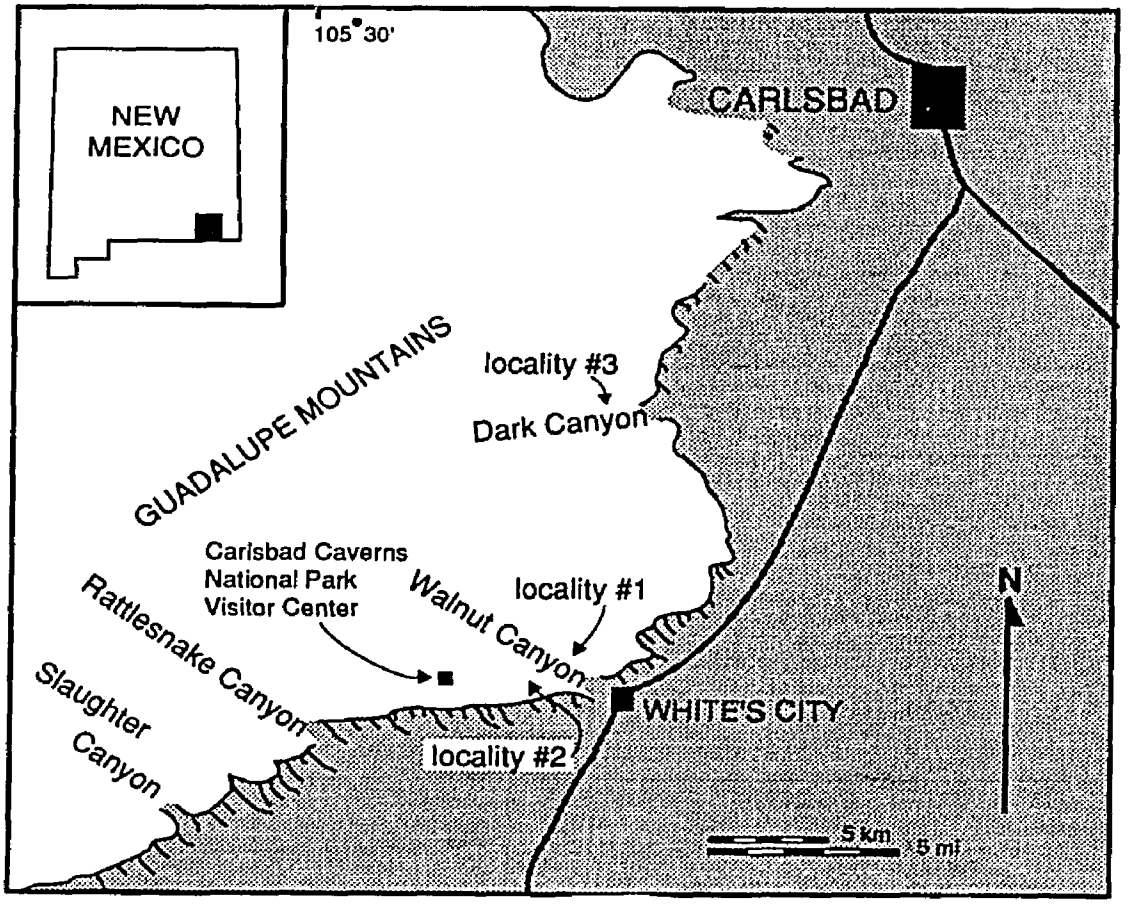


Fig. 2.2. Map of the study area showing configuration of the Guadalupe Mountains and sample localities. Modified from King (1948).

reef complex, but at this time detailed studies are unavailable (Liu and coworkers, pers. commun.). Smaller populations of other reef dwellers including foraminifera, gastropods, and tabulate and rugose corals have less potential as paleoenvironmental indicators, either because they are not abundant or because their modern analogs live in a wide variety of disparate environments.

In contrast, green algae of the family Dasycladaceae are abundant in the Capitan reef and associated facies. They have modern analogs and have great potential as paleoenvironmental indicators. Dasyclads, usually *Mizzia*, are present in the most shelfward zones of the massive reef and are abundant in the bedded rocks immediately shelfward of the reef. Dasyclads are the dominant fossils (commonly the only fossil) throughout tens of meters of section in the bedded backreef facies (i.e. the Tansill, Yates, and Seven Rivers Formations) immediately shelfward of the Capitan Formation (Fig. 2.1).

The fossil genus *Mizzia* has a remarkable analog in the modern genus *Cymopolia* (Rezak 1959). Although *Mizzia* and *Cymopolia* are assigned to different tribes because of the absence of preserved sporangia in *Mizzia*, the striking morphological similarity is worthy of further consideration. The genus *Mizzia* is confined to the Permian, reached greatest generic diversity during the Middle to Late Permian (Johnson 1961), and existed for about 40 million years (Palmer 1983). The stratigraphic range for the extant genus *Cymopolia* is Cretaceous to Holocene or about 140 million years (Johnson 1961).

The general environmental factors controlling the distribution of dasyclads are well documented. Most modern dasyclads are restricted to a limited range of environments. They live in tropical to subtropical waters,

on muddy, sandy, or solid substrates, and in protected low-energy environments (Flügel 1985). In addition, dasyclads can tolerate a remarkably wide range of salinities (<2 ppt to >120 ppt) and may be very abundant in waters too saline or too brackish for habitation by other marine organisms (Beadle 1988). Dasyclads generally are found at depths from just below low tide to about 30 m, and most commonly are found at depths <5 m (Flügel 1985). These general criteria for extant members of the family Dasycladaceae should not be used as the sole basis for interpretation of the paleoenvironment of fossil dasyclads. Because much habitat diversity exists among modern dasyclads and probably also existed among their fossil counterparts, each occurrence should be evaluated independently taking all evidence into account (Elliot 1978). With this in mind, the goal of this study is to gather all possible information in order to evaluate the habitat of the abundant *Mizzia* fossils in the sediments immediately shelfward of the Capitan Formation in the Guadalupe Mountains.

MATERIALS AND METHODS

Collection of specimens. Fossil dasyclads were collected in 1987 and 1988 from three localities in the Guadalupe Mountains of southeastern New Mexico (Figs. 2.2, 2.3). The majority of samples were collected just inside the boundary of Carlsbad Caverns National Park (with permission from the National Park Service). The first locality was 19 km southwest

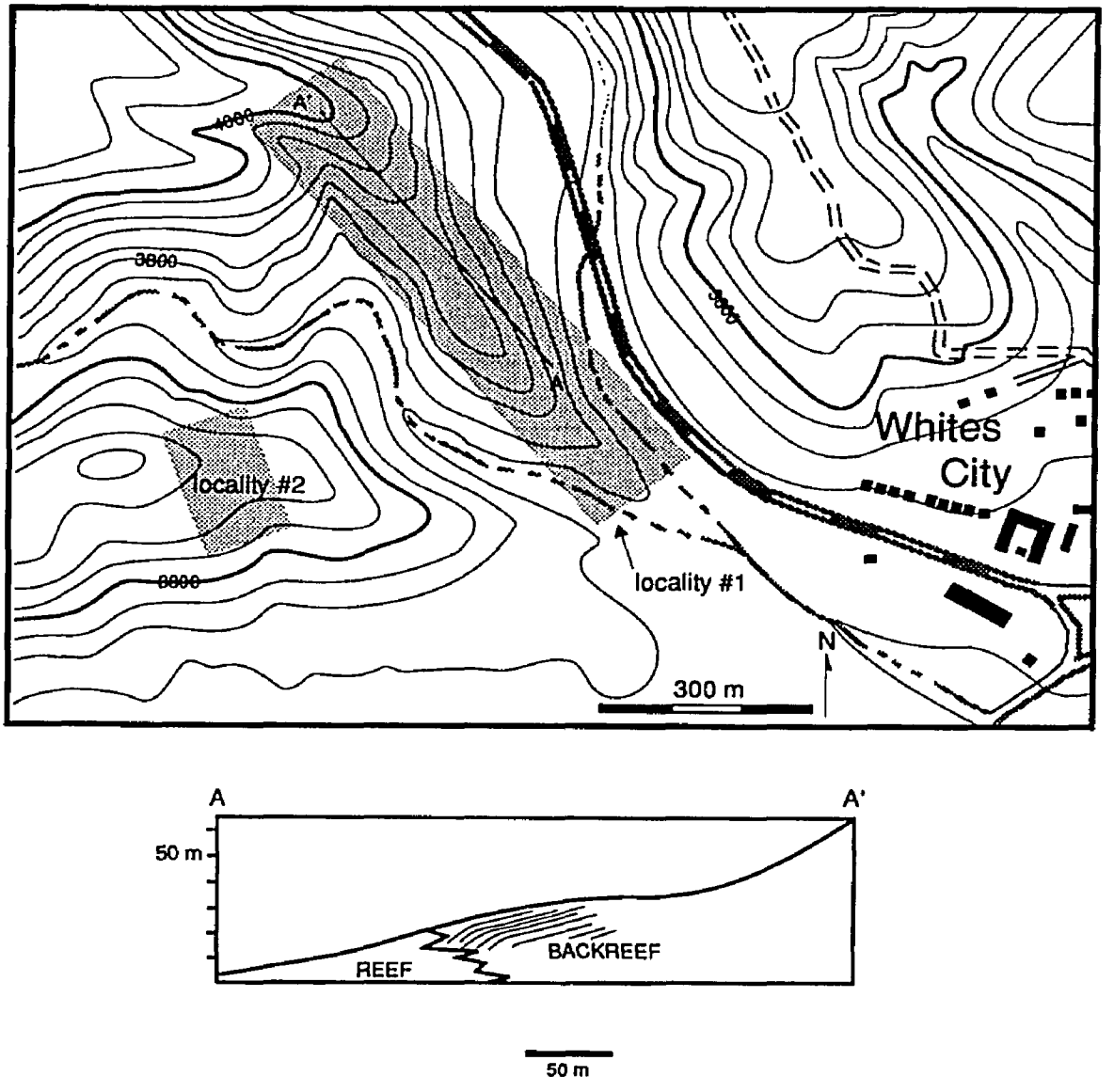


Fig. 2.3. Topographic map of the main study area and topographic profile of the south face of Walnut Canyon. Reef to backreef transition and backreef bedding are sketched schematically.

of Carlsbad, New Mexico on the south wall of Walnut Canyon near the mouth of the canyon. The second locality was along a recreational trail 0.5 km to the south of the first locality. The third locality was 10 km southwest of Carlsbad, New Mexico on the north wall near the mouth of Dark Canyon. Most samples were taken from outcrops at 3-m intervals along measured transects. Seven of the samples studied were selected from eroded debris where natural weathering by rain water and organic acids had revealed structural details of dasyclad fossils. The precise location of each sample was marked on enlarged photographs of the canyon wall or on a U.S. Geological Survey 7.5 minute quadrangle map.

Section preparation. Rock samples were cut into 45x25x10 mm blocks with masonry and trim saws. Each sample was impregnated with Ciba-Geigy Araldite 506 blue-dyed epoxy resin, and one side was polished. The polished side was then mounted onto a glass slide with Hilquist epoxy resin. The epoxy has an index of refraction equal to the reference standard, quartz. A Hilquist thin section machine was used to cut off most of the block and grind the remaining section to a workable thickness, approximately 200 μm. Final preparation was done with the Logitech Automated Thin Section Production System (Logitech LP 30 and Logitech WG2A). Although standard geologic thin sections are precisely 30 μm thick; slightly thicker sections, 35-40 μm, revealed more structural detail.

Preserved samples of *Cymopolia*, collected in Florida between 1980-1984, were obtained from the teaching collection in the Department of Botany at Louisiana State University, Baton Rouge, Louisiana. Samples were rinsed with distilled water to remove as much preservative (FAA) as possible and then treated twice with 30% hydrogen peroxide to remove organic matter. The remaining aragonitic ($CaCO_3$) skeleton was mounted

in Ciba-Geigy Araldite 506, blue-dyed epoxy resin. Thin sections of the cured epoxy blocks were prepared using the same technique as described for the fossil specimens.

Examination of samples. Both the structure of *Mizzia* fossils in naturally weathered hand samples, i.e. small pieces of rock collected in the field (Figs. 2.6, 2.8, 2.10), and the calcareous skeleton of *Cymopolia* segments (Figs. 2.7, 2.9) were studied and photographed with binocular microscopes and a scanning electron microscope (SEM). Thin sections of fossil and modern specimens were studied and photographed with petrographic microscopes.

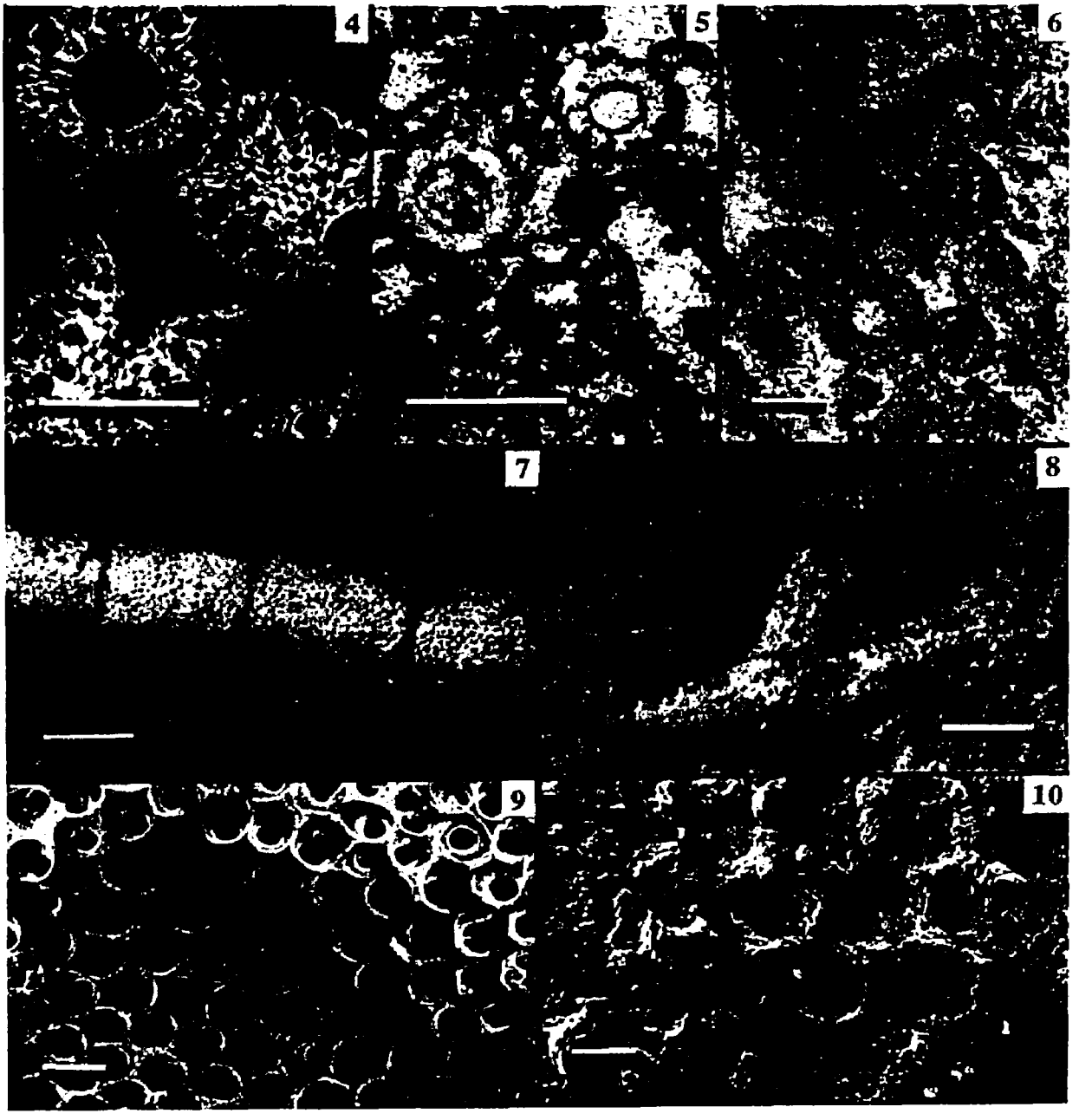
RESULTS

Morphology

Like all members of the family Dasycladaceae, *Mizzia* and *Cymopolia* are radially symmetrical (Figs. 2.4-2.6) with a large central axis (stem cell) and one or more whorls of branches (Wray 1977). The most obvious similarity between *Mizzia* and *Cymopolia* is the articulated thallus composed of round to barrel-shaped segments. This type of thallus, termed moniliform, is similar to a pearl necklace. Joints, i.e. uncalcified regions (Fig. 2.7, 2.8), allow for flexibility (Bassoullet et al. 1977).

Mizzia is most often found as disarticulated segments, and *Cymopolia* is known to quickly disarticulate into segments after death (Wray 1977). In the sections studied, *Mizzia* segments had a mean diameter

Figs. 2.4-2.10. Photographs illustrating the morphological similarities between *Mizzia* and *Cymopolia*. Figs. 2.4, 2.5. Petrographic microscope. Scale bars=1mm. Fig. 2.4. Calcareous portion of *Cymopolia* segments in thin section; crossed polarized light. Fig. 2.5. *Mizzia* fossil in thin section; plane polarized light. Sample from Dark Canyon (locality 3). Figs. 2.6-2.8. Binocular microscope. Scale bars=1mm. Fig. 2.6. Disarticulated *Mizzia* segments in naturally weathered surface. Sample from Walnut Canyon immediately shelfward of the reef (locality 1). Fig. 2.7. Articulated, branched portion of *Cymopolia* thallus. Fig. 2.8. Articulated portion of *Mizzia* thallus. Sample from Dark Canyon (locality 3). Figs. 2.9, 2.10 Scanning electron micrographs. Scale bars=100μm. Fig. 9. Calcareous portion of *Cymopolia* segment. Fig. 2.10. Portion of *Mizzia* segment in naturally weathered surface. Original mesh of needle-like aragonite crystals has been replaced by blocky calcite crystals.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of 0.84 mm (SD ±0.23), and *Cymopolia* segments had a mean diameter of 1.0 mm (SD ±0.18). Sampling was biased toward well preserved, articulated specimens. Of the 25 fossil samples studied, four contained articulated segments. Two of these were hand samples each containing a number of articulated sections of *Mizzia* plants. On one of these slabs the sections of articulated thallus were up to 1 cm long; the segment diameter in each section varied. At least two of these sections appeared to be branched. Preservation was poor, but a similar pattern was repeated several times in one sample (Fig. 2.8).

Mizzia and *Cymopolia* both have a euspondyle cortex; that is, the branches are arranged in regularly spaced whorls, each whorl in a preferred plane, along a central axis. The bulbous, enlarged tips of the whorls meet each other to form the cortex. Calcification is external to the cell, and the calcareous skeleton has a honeycomb pattern (Figs. 2.9, 2.10). The outer cortex of *Cymopolia* is easily abraded, and the individual segments are easily broken or crushed. In the majority of the samples studied the outer cortex of *Mizzia* showed little sign of abrasion. The percentage of broken *Mizzia* segments was consistently low (average 10%, range 0-25%).

Habitat of Extant Cymopolia

Living *Cymopolia* are reported from the Caribbean, the Mediterranean, the Gulf of Mexico, the Canary Islands, and the Pacific (Britton and Millspaugh 1920, Valet 1969, Hurtado-Ponce and Modelo 1983). The organism is found just below tide base in warm (20-30° C) water (Hämmerling 1944, Woelkerling 1976) and attaches itself to hard substrates in moderately agitated water (Britton and Millspaugh 1920).

Reconstruction of Habitat

Evidence from paleolatitude. When occurrences of *Mizzia* are plotted on a Late Permian plate-tectonic reconstruction of the continents, they generally fall between 30° north and south latitude (Flügel 1985). Thus, *Mizzia*, like *Cymopolia* and other modern dasyclads, probably lived in warm, tropical to subtropical waters.

Evidence from lithology. To a geologist, lithology is usually the single most useful line of evidence for the determination of paleoenvironment. For some dasyclads lithology may be even more significant because a correlation may exist between sediment type and dasyclad species present. This correlation is related to turbulence, light intensity, and salinity (Zorn 1976). Unfortunately, in the Guadalupe Mountains such a correlation is not obvious.

In the Guadalupe Mountains, however, the variety and distribution of lithologic types among *Mizzia*-bearing rocks is significant. *Mizzia* is found in grainstones, packstones, and wackestones. A grainstone, by definition, is a rock containing no more than 1% fine (<20 μ) particles. A packstone contains more than 1% fine particles and is grain supported. A wackestone contains more than 10% grains and is mud supported (Dunham 1962). Rocks described as packstones and grainstones were deposited in conditions where fine particles were carried away by currents, or no fine particles were present. Rocks described as wackestones were deposited in conditions where current energies were too low to remove fine particles.

Grainstones and packstones composed of disarticulated dasyclad segments (Fig. 2.5, 2.6) are found at the mouth of Walnut Canyon and the mouth of Dark Canyon, immediately shelfward of the reef (localities 1, 3; Figs. 2.2, 2.3). Dasyclad wackestones were found in Walnut Canyon

further shelfward of the reef (northern most portion of locality 1; Fig. 2.3). Perhaps the most significant lithologies are mud-rich packstones and wackestones containing articulated sections of thalli (Fig. 2.8). These samples were found shelfward of the mouth of Dark Canyon and also south of Walnut Canyon along the Gudalupe Mountains escarpment, shelfward of the reef (localities 2, 3; Figs. 2.2, 2.3).

Field relationships and information from other areas are useful in interpretation of the distribution of these lithologies. The Capitan and associated formations are preserved in the subsurface to the east of the Guadalupe Mountains. Paleochannels cutting through the reef are preserved in the subsurface (Silver and Todd 1969). This feature and field evidence collected as part of this study, suggest that the location of canyons in the Guadalupe Mountains may have been controlled by paleochannels. Rocks composed of disarticulated dasyclad segments are interpreted as having been deposited in grainstones and packstones in high energy conditions along paleochannels (now canyons) that cut through the reef. At locality 2 near Walnut Canyon (Figs. 2.2, 2.3), the mud-rich packstones containing articulated dasyclads were deposited in low energy, muddy environments shelfward of the reef and away from the paleochannel. Articulated dasyclads are also found shelfward of the reef in Dark Canyon. Pray (pers. commun. 1989), believes that the area around Dark Canyon was located in an embayment (Fig. 2.2) and energy conditions were lower there than at other places along the reef. Lower current energies along this paleochannel (now Dark Canyon) would have allowed for the preservation of articulated dasyclads.

Evidence from population diversity. Additional key factors in this reconstruction of paleoenvironment are the distribution and nature of the

dasyclad populations in the Guadalupe Mountains, where the most striking feature of the dasyclad-dominated grainstones and packstones is their low diversity. Many samples are monospecific, dominated exclusively by *Mizzia* (*M.velebitana* (?)) Schubert, 1907). The genera *Macroporella* Pia, 1912 and *Gymnocodium* (?) Pia, 1920 are also present and occasionally dominate individual samples. Associated fauna includes abundant micritic (i.e. muddy-looking) encrustations, most of which are probably related to blue green algae, although some have structures similar to encrusting foraminifera or to the problematic organism *Tubiphytes*. Other fossils include gastropods, fragments of bivalve shells, foraminifera, sporadic ostracods, and in one section, an echinoderm fragment. Zones of intact brachiopods are found in outcrops near the reef but are not found further shelfward in the back reef. Fusilinid foraminifera are sporadically present, but not abundant, in the Tansill Formation facies studied in Walnut and Dark Canyons. Zones dominated entirely by fusilinids are present, however, in the Yates and Seven Rivers Formations. The assemblage and level of diversity present in the Tansill Formation are consistent with a hypersaline environment.

Evidence from distribution. The distribution of *Mizzia* fossils in the outcrops is also striking. The transition from the remarkably high-diversity sponge and algal assemblage in the reef into the remarkably low-diversity dasyclad-dominated assemblage in the back reef is abrupt (Fig. 2.3). In at least one locality on the south wall of Walnut Canyon this transition occurs over a distance as short as 10 m. This abrupt transition into a dasyclad-dominated assemblage seen in the Tansill Formation is repeated in the Yates Formation in Rattlesnake Canyon and in the Seven Rivers Formation in Slaughter Canyon. Abrupt facies and faunal changes

are typical of reef to back reef transitions in modern settings due to an abrupt loss in energy (75-98%) as waves strike the reef and cross into the back reef (Roberts et al. 1975).

Depth. In attempting to reconstruct the paleoenvironment of Mizzia in the Guadalupe Mountains, depth is a difficult environmental parameter to deduce. Like all green algae, dasyclads are dependent on the red end of the light spectrum, which is 90% absorbed in the top 20 m of the ocean (Ginsburg et al. 1972). The deepest reported occurrence of a modern dasyclad is that of *Dasycladus* at 90 m in the Persian Gulf (Elliott 1977). Such an occurrence is rare; most dasyclads are found in much shallower water (<30 m), and virtually all prolific growths are found in shallow water. For example, *Cymopolia* grows in abundance just below low tide mark. The great abundance of *Mizzia* in the back reef facies of the Guadalupe Mountains is consistent with the suggestion that *Mizzia* also grew in shallow water. A conservative estimate based on comparison to modern analogs would be that where *Mizzia* grew in profusion, waters were less than 30 m deep (probably much less).

Wave action. Assessing the amount of wave action in the *Mizzia* paleoenvironment is relatively straightforward. Wave action may result in low species diversity; for example, the coral *Acropora palmata* dominates the upper, high-energy zone of most Caribbean reefs and the red alga *Lithothamnium* dominates a similar zone in Pacific reefs. However, wave action is discounted as a limiting factor in the back reef beds of the Tansill Formation of the Guadalupe Mountains because the percentage of broken *Mizzia* fragments is low (average 10%). Even fragments that showed distinct signs of abrasion are rare, and as Elliott (1978) has suggested, the degree of destruction of the outer layer of aragonite is indicative of current

activity. Waves strong enough to limit diversity should result in a much higher percentage of broken and abraded fragments.

Additional evidence against wave action as a limiting factor for *Mizzia* comes from comparison with *Cymopolia*. Most dasyclads live in calm or moderately agitated water, and *Cymopolia* thrives in the latter. It is possible that the morphology of *Cymopolia*, and by comparison *Mizzia*, is an adaption to low or moderate energy environments, not high current energies. Whether one accepts this idea or not, the fact remains that articulated sections were found in local accumulations in the Guadalupe Mountains. Thus, at least in local pockets, current energies in the Guadalupe Mountains must have been very low to permit this type of preservation. Although the dasyclad grainstones in the Guadalupe Mountains are currently considered to be a classic example of winnowed platform-edge sands (Wilson 1975), this interpretation is not consistent with the data provided by these algal fossils.

Hypersalinity. Hypersalinity may result in domination by one species, for example *Acetabularia* dominated lagoons. An ancient dasyclad-dominated environment might have resulted in the deposition of a dasyclad-dominated rock. Thus, hypersalinity has also been cited as a possible controlling factor in the formation of dasyclad grainstones from Permian and Triassic strata around the world (Beadle 1988). Modern, low diversity, dasyclad-dominated environments have associated faunas of ostracodes, formaminifera, and small mollusks, just as do many ancient dasyclad grainstones, including those from the Guadalupe Mountains (Beadle 1988).

Because reconstructions place the Permian Basin near the equator in the southern part of the northern trade-wind belt (Fischer and Sarnthein

1988), it is reasonable to assume that climatic conditions in southeastern New Mexico during the Late Permian were extremely arid. This assumption is supported by the prescence of evaporites (rocks formed by chemical precipitation of sufate and halide minerals from sea water) in the Tansill Formation preserved in the subsurface on the eastern margin of the Delaware basin (Silver and Todd 1969). These protected subsurface evaporites are equivalent to the exposed Tansill Formation outcrops in the Guadalupe Mountains. Additional evidence for hypersaline conditions comes from isotopic analyses of interstitial cements (Given and Lohmann 1985) that indicate an increase in salinity of marine waters near the end of Capitan deposition. These isotopic and subsurface data lead to the conclusion that conditions in the Guadalupe Mountains were certainly arid; evaporites probably formed in inner shelf lagoons contemporaneously with the deposition of dasyclad grainstones immediately shelfward of the reef. The association of these lithologies is significant to an environmental interpretation of *Mizzia,* and it is not unique to the Guadalupe Mountains. *Mizzia* grainstones and contemporaneous evaporite deposition are also reported from the Upper Permian Zechstein Formation of Northern Europe (Clark 1980).

Summary of Results.

We conclude that *Mizzia,* where it is found in the Guadalupe Mountains and probably at other localities throughout the world, thrived in a habitat that was warm, at most moderately agitated, sometimes restricted (i.e. protected), probably shallow, and probably hypersaline (Fig. 2.11). This interpretation has important implications concerning the type of reef found in the Capitan complex. We propose that the Capitan reef, which contains a striking volume of in-place, frame-building and binding

organisms with abundant porosity-filling cement, grew to sea level and blocked vigorous wave action. Just as in modern reef settings, this situation created a shallow, protected lagoon immediately shelfward of the reef. Because conditions were extremely arid, these shallow waters quickly became hypersaline. This shallow, protected, hypersaline environment provided ideal conditions for prolific growth of dasyclads.

DISCUSSION

The comparison of the Capitan reef complex to a modern barrier reef is not a new concept. The earliest general studies of this area (Lloyd 1929, King 1948, Newell et al. 1953) came to similar conclusions. Later studies focusing on algae, lithologic types, and their distribution also concluded that the Capitan reef complex is similar to modern barrier reefs (Klement 1966, Cys, 1971, Cronoble, 1947) (Fig. 2.12 A). A different model, however, has dominated the literature for the last 20 years (Fig. 2.12 B). According to the marginal mound hypothesis, (Achauer 1969, Dunham 1972, Pray 1986) the Capitan reef complex is an "example of massive limestone formed at a submerged shelf edge" (Pray 1986). The terminology "marginal mound" implies not a wave-resistant reef but an accumulation of sediment forming in deep water (below wave base). This model implies that the sediments deposited shelfward of the reef were open to oceanic circulation and wave action. It does not allow for restriction of flow nor for creation of hypersaline conditions immediately shelfward of the reef. Many detailed theses and dissertations support the "marginal mound" hypothesis (Babcock 1974, Yurewicz 1976, Hurley 1978, Neese 1979, Schwartz 1981). They have all focused on specific areas, never on *Mizzia*-dominated zones, and none have fully explained the unique distribution of dasyclads in this area.

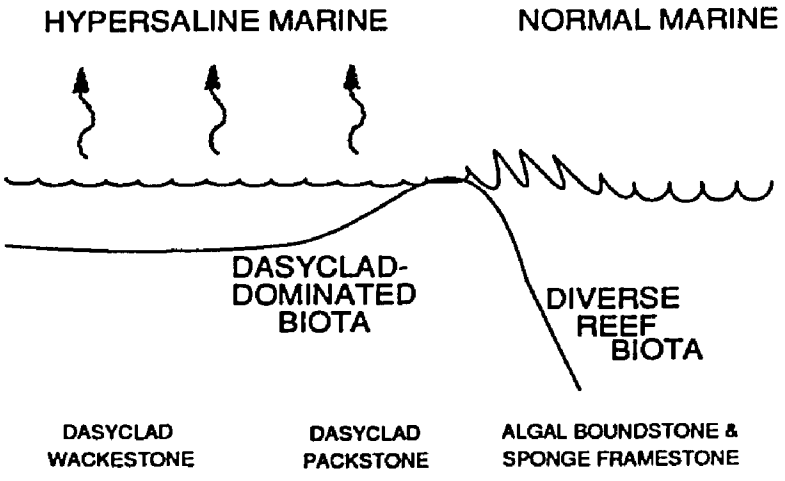

Fig. 2.11. Schematic cross section through reef and backreef showing relative water energies and distribution of lithologies.

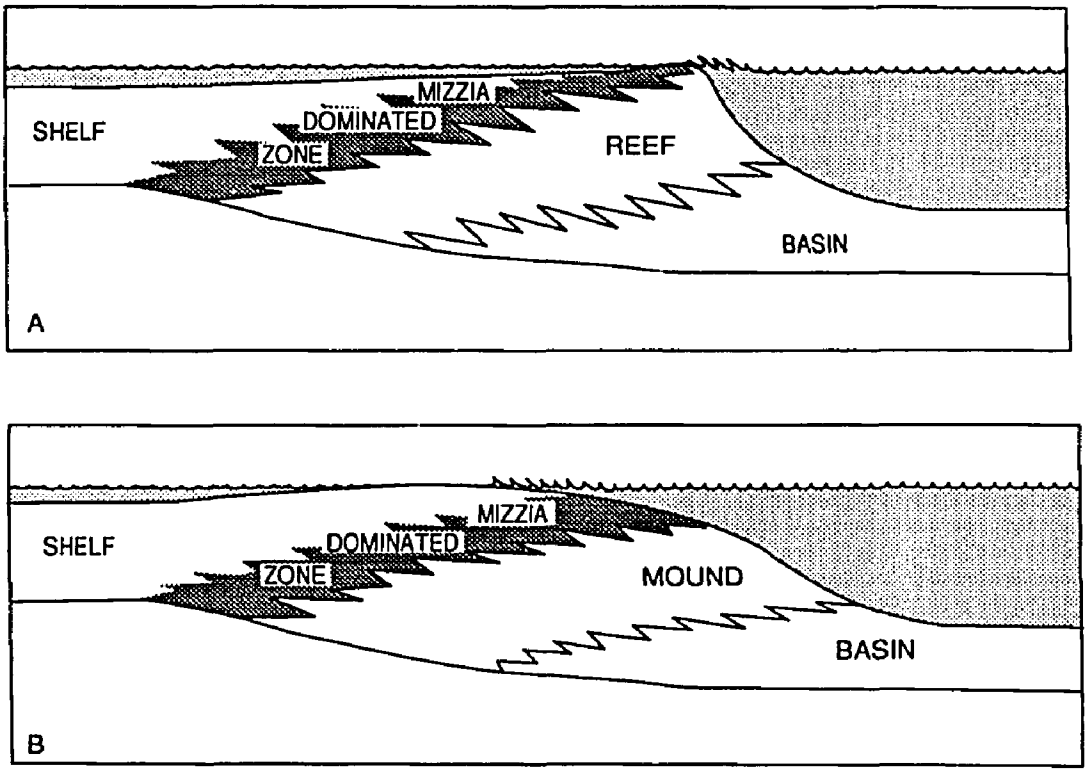

Fig. 2.12. Schematic diagrams. A) Original barrier reef model of deposition for the Capitan reef complex simplified from Newell et al. (1953). B) Marginal mound depositional model simplified from Dunham (1972).

We suggest that the marginal mound hypothesis must either be modified to explain the distribution of dasyclads or it must be abandoned. We also note that many major advances in understanding carbonate rocks have come about since the marginal mound model was proposed in the late 1960's. This paper is a precursor to a much broader study which will incorporate many of these new advances including the chemistry and mechanics of cement deposition, dynamics of modern reef circulation, the relationship of reef growth to sea level change, and a better understanding of the "phylloid" algae (*Eugonophyllum* and *Archeolithoporella*). We hope that further research will show conclusively which model is correct.

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CHAPTER IV

The Capitan Formation and Carlsbad Group, Guadalupe Mountains, southeastern New Mexico and West Texas: a barrier reef complex

INTRODUCTION

The Guadalupe Mountain region of southeastern New Mexico contains magnificent exposures of basin, slope, shelf-margin, and shelf sediments of Permian age (Fig. 3.1). Many outcrops are easily accessible, and the region has been the subject of hundreds of geological studies. Despite this intensive study, the depositional setting of the shelf-margin buildup, mapped as the Capitan Formation, remains a point of controversy. In addition, questions remain about the mechanism of deposition of the shelfward lithologies mapped as the Carlsbad Group (in ascending order the Seven Rivers, Yates, and Tansill formations) (Fig. 3.2).

Early studies of the Capitan Formation described it as a shallow-water reef, similar to a modern barrier reef (Lloyd, 1929; Johnson, 1942; Newell et al., 1953) (Fig. 3.3a). Beginning in the 1960's, the Capitan was described as a marginal mound (Fig. 3.3b) (Achauer, 1969; Dunham, 1972). This model suggests that throughout its deposition, the Capitan reef formed at depths below wave base (10-45 m) (Babcock and Yurewicz, 1989). The concentration of pisoids and tepee structures found shelfward of the margin are considered to have formed at the paleotopographic shelf-crest, restricting circulation, and leading to deposition of evaporites in the inner shelf (Esteban and Pray, 1983). The model for deposition of the Capitan complex presented below is in agreement with the early studies of the area and is incompatible with the marginal mound hypothesis.

In this paper we show that the Capitan reef is clearly analogous to a modern framework reef. It contains a diverse array of frame-building and binding organisms, evidence for bioerosion, and abundant internal sediment. In addition, the Capitan contains abundant, originally aragonitic marine cement. The distribution of that cement parallels the distribution of

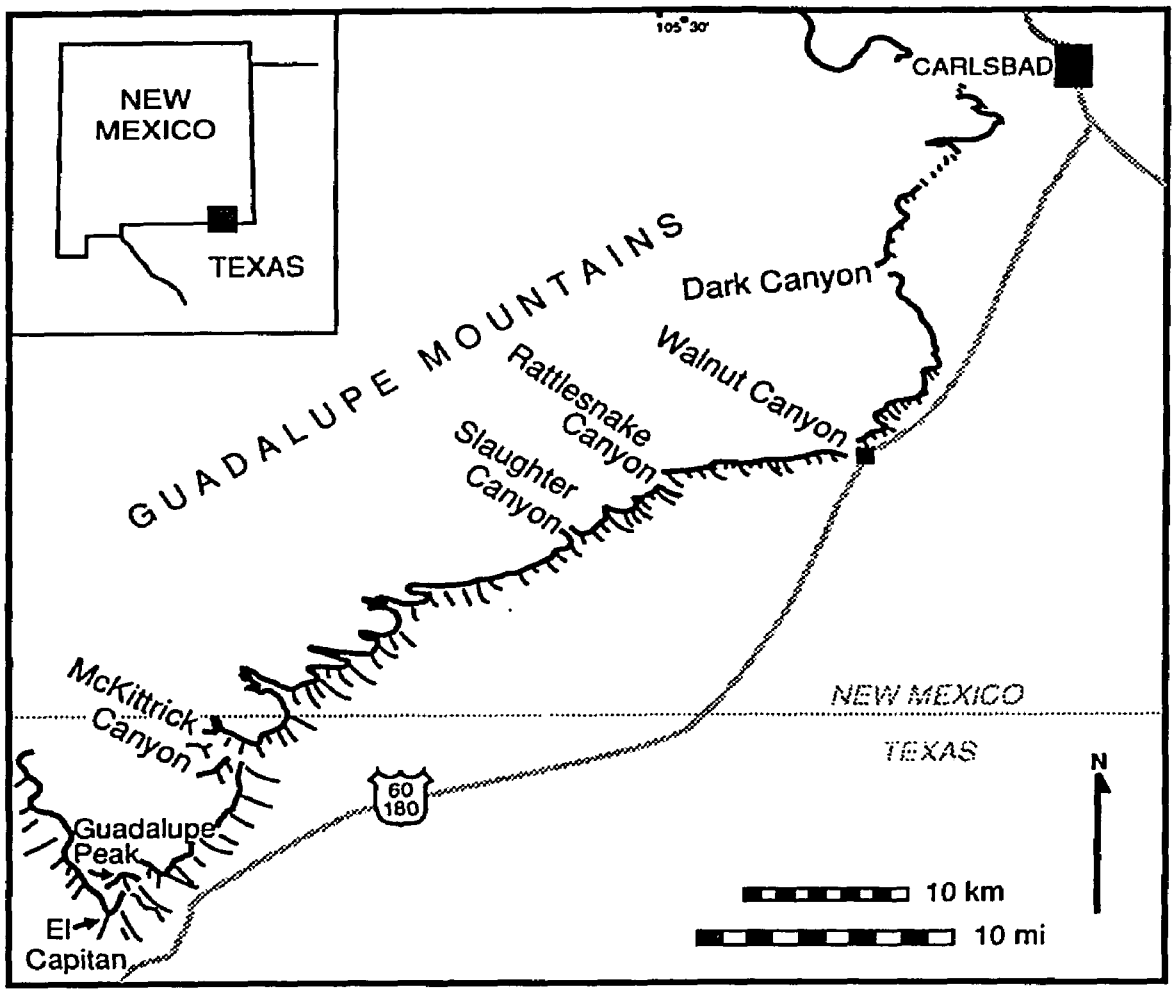


Figure 3.1. Map of the study area (Modified from King, 1948).

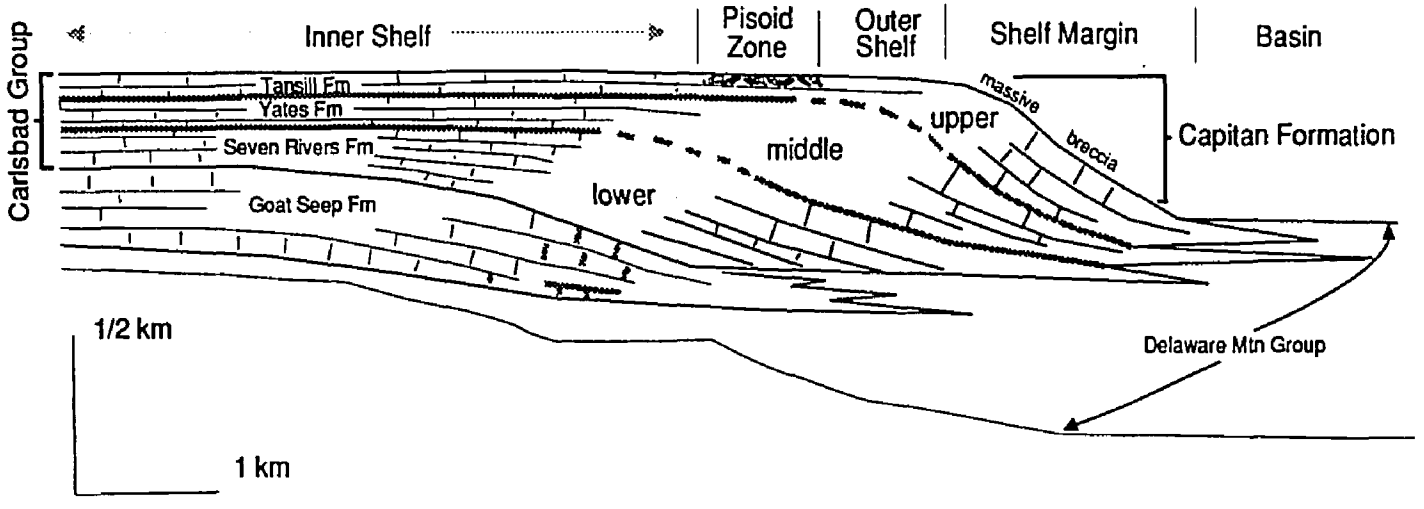


Figure 3.2. Stratigraphic chart illustrating divisions of Capitan Formation, associated members of the Carlsbad Group (after Babcock and Yurewicz, 1989), and subdivision of the shelf (after Esteban and Pray 1983).

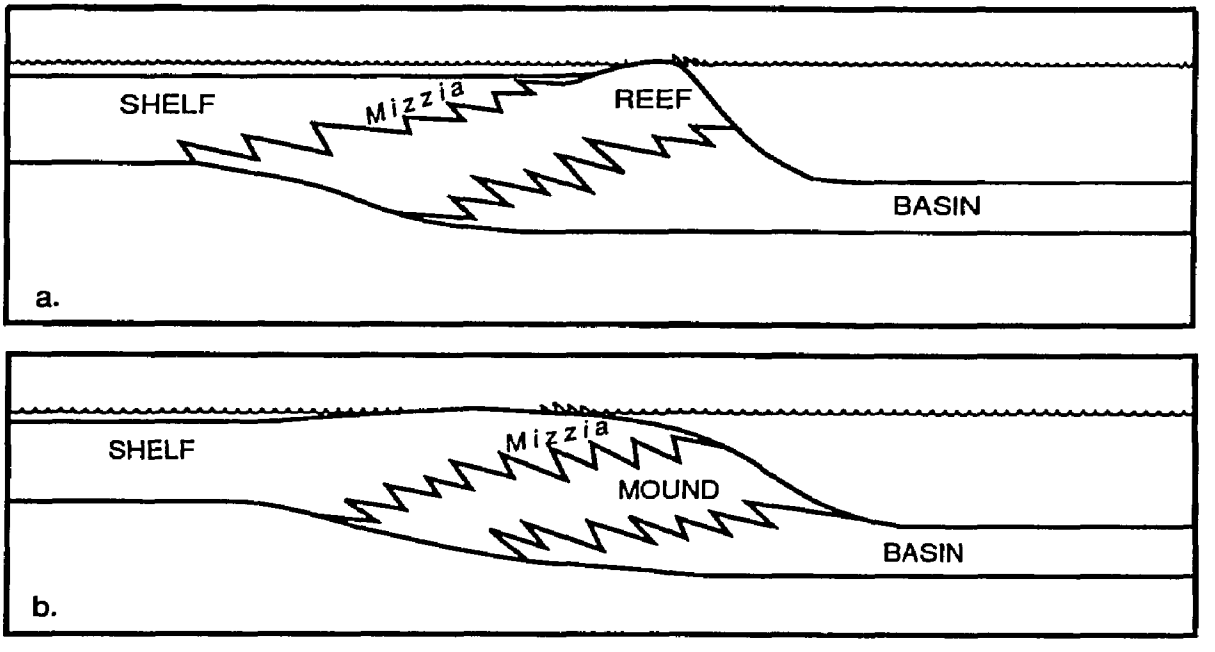


Figure 3.3. (a) Schematic cross section illustrating barrier reef hypothesis (After King, 1948; Newell *et al.*, 1953). (b) Schematic cross section illustrating marginal mound hypothesis (After Dunham, 1972). Note the location of breaking waves in each diagram.

marine cement in a modern reef (Shinn, 1969; Lighty, 1985). Throughout most of the Capitan section, there is an abrupt transition between the massive boundstones of the shelf margin and the bedded grainstones and packstones of the outer shelf. Biota present in the outer-shelf deposits are characteristic of restricted, slightly hypersaline conditions. In addition, mud content in these rocks increases shelfward, suggesting deposition in a quiet backreef lagoon. Further evidence of a shallow-water, barrier reef are large-scale geomorphic features identical to those in modern reefs. The barrier reef model is the best-fit hypothesis for the data available.

The significance of this report is multifold. First, a revised depositional model for the Capitan reef complex of the Guadalupe Mountains is directly relevant to petroleum exploration and production in West Texas (Fig. 3.4). Second, this model is potentially applicable to economic exploitation of other ancient reef systems. Third, this paper shows that the Permian was indeed a time of reef building and not a time when only bioherms developed, as previously assumed (James, 1983). Fourth, this area is described in numerous textbooks (e.g., Wilson, 1975; Stanley, 1986; Moore, 1989; Tucker and Wright, 1990) and it is used as a "field classroom" by hundreds of professional and student geologists annually.

History of study and concepts

The extensive literature on the Guadalupe Mountains traces the development of the concepts of reef versus bioherm. Although a complete review of the literature is beyond the scope of this paper, the following section highlights the major investigators and their contributions to the developing controversy.

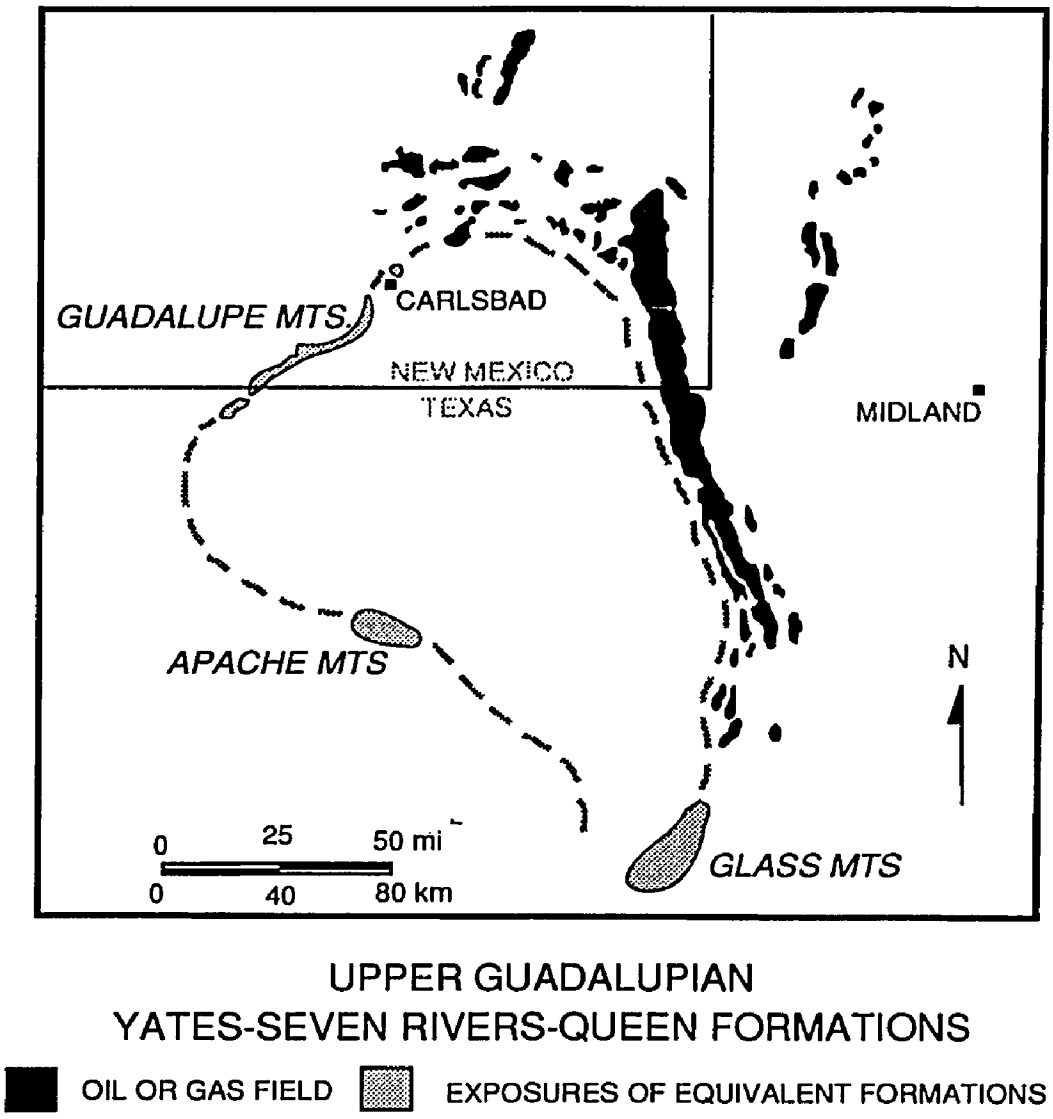


Figure 3.4. Map illustrating Delaware Basin and relative location Carlsbad Group outcrop and hydrocarbon production (Simplified from Ward *et al.*, 1987).

Girty (1908) studied the fauna of the Guadalupe Mountains. Although outdated, this study remains significant because it is the sole comprehensive study devoted exclusively to identification of the biota of the Capitan Formation, and because it is still an important resource for study of some fossil components of the Capitan, particularly the sponges and brachiopods. Lloyd (1929) was the first to compare, in depth, the Capitan Formation to a modern barrier reef. He described the Capitan as a reef based in part on the massive nature of the Capitan in marked contrast to the, fine-grained, thin-bedded facies of the shelf. Crandall (1929) also interpreted the Capitan Formation as a reef.

Johnson (1942) prepared systematic descriptions of algae from 11 sites in the Guadalupe Mountains and one site in the Apache Mountains. Included in this work is an idealized reef-profile for the Capitan based on comparison to modern reefs, algal types present, and associated biotic assemblages.

King (1948) used the word "reef" in reference to the Capitan, but questioned Johnson's detailed facies division as being too heavily dependent on comparison to modern reefs and, perhaps, inadequately substantiated. King's own study, based on extensive field work, remains a valuable source of information on the stratigraphy and tectonic history of the area.

The most extensive study based on the hypothesis that the Capitan was a barrier reef was carried out by a team of scientist directed by N. D. Newell (1953). This paleoccological study of the Guadalupe Mountains uses paleontological, petrologic, and stratigraphic criteria to establish environmental conditions associated with deposition of the Capitan Formation. It compares the Capitan to modern and ancient reef systems. Unfortunately, the study presents only limited paleontologic data on the

Gudalupe Mountains (lists of species and their distributions). Almost 40 years later, no detailed, comprehensive paleontological study exists, although several excellent studies of small areas are available (e.g., J. Babcock, 1974; L. Babcock, 1974).

Klement (1966) also referred to the Capitan as a reef. He compared the distribution of modern algae in Florida to the distribution of algae in the Guadalupe Mountains, and used the distribution of the Guadalupe Mountains algae to delineate depositional environments. He based his divisions on the presence of red algae in the reef and green algae and stromatolites shelfward of the reef in a depositional environment he considered analogous to the backreef lagoons of the Florida Keys.

Cys (1971) also believed that the Capitan Formation was an organic/ecologic reef. He argued that: 1) the massive member of the Capitan occurs at the shelf break above bedded slope-deposits, 2) framebuilding organisms are present, though often recrystallized, and 3) the Capitan must have formed a shelf-edge barrier if it were to have created a shallow protected lagoon on the shelf. Cys' discussion was written in response to a paper by Achauer (1969) proposing a new model for deposition of the Capitan Formation. For the next 20 years, Achauer's hypothesis, often termed the "marginal mound model," became the accepted working hypothesis for most studies of the Capitan.

Before beginning a discussion of the marginal mound hypothesis, it is important to define the terms involved. A "mound" refers to an equidimensional or ellipsoidal carbonate buildup. A "bioherm" refers to a laterally restricted accumulation of sediment. An "organic bank" has an internal composition that allows the inference that it is formed mostly of detrital organic sediment that accumulated in place by trapping or baffling,

but also in part by mechanical accumulation by waves and currents (Wilson, 1975). A "stratigraphic" or "geologic" reef is a carbonate buildup or mass of varying geometry (Dunham, 1970) that may be organically or inorganically bound (Wilson, 1975). It is a three-dimensional feature and an objective (not subjective) term (Dunham, 1970). In contrast, Dunham (1970) suggested that the term "ecologic reef" was subjective. An "ecologic reef" is built of framebuilding and binding organisms, stands above the sea floor, and is wave -resistant (Lowenstamm, 1950). In addition to framebuilders and binders, wave-resistant framework reefs contain internal sediment, derived in part by the activity of bioeroding organisms, and cement (Ginsburg and Lowenstamm, 1958; Moore, 1989). Each of these terms has been used in reference to the Capitan Formation.

Achauer (1969) proposed that the Capitan was not a barrier reef but instead a linear organic bank. He worked with 18 measured sections, sampled at 10-20 ft intervals, in McKittrick and Slaughter Canyons (Fig. 3.1). He considered the few fossils he found in growth-position to be organisms incapable of creating a wave-resistant framework. He noted a dominance of bioclastic skeletal debris in samples of the reef massive.

Dunham (1970) applied Achauer's (1969) organic bank model to the Capitan in his discussion of the terminology for reefs versus bioherms, and he expanded on the idea in his guidebook on the Guadalupe Mountains (Dunham, 1972). Dunham suggested that the Capitan Formation was probably originally dominated by aragonite (Dunham, 1972, p. II-3). Only later were the marine, previously aragonitic cements recognized (Schmidt, 1977; Mazzullo and Cys, 1979). Dunham (1972) described the dominant lithology of the Capitan as sponge wackestone, but he noted that with a

strict adherence to his classification system some samples would be called "packstone" or "grainstone" (Dunham, 1972, p. II-45). Dunham believed that the abundant pisoids found shelfward of the reef were early vadose concretions formed by subaerial exposure and calichification of carbonate facies (Dunham, 1969). He took this as evidence of repeated subaerial exposure of the pisoid facies, and having found no similar evidence for exposure within the reef facies, he concluded that the pisoids formed the topographic crest of the complex and that the reef was located on the slope topographically below the shelf crest. Dunham's hypothesis for pisoid formation was seriously questioned by Esteban and Pray (1976; 1977) who proposed that the pisoids formed subaqueously in shallow, subtidal hypersaline water.

Even though many observations on which the marginal mound hypothesis was based were subsequently questioned, the marginal mound model, as proposed by Achauer (1969) and Dunham (1972), remained the working hypothesis during acquisition of a large body of observations on the Guadalupe Mountains. Many of these observations were compiled by students under the direction of L. C. Pray at the University of Wisconsin, Madison. This data-base consists of more than twenty theses and dissertations. Only those studies directly applicable to the present discussion of the Capitan Formation and the Carlsbad Group will be considered here.

J. Babcock (1974, 1977) studied the upper Capitan (Fig. 3.2) along the Guadalupe Mountains escarpment, and focused on the types of algae present and their roles in the genesis of the Capitan Formation. His identification and description of algae and organisms of uncertain affinities proved important to understanding the nature of the Capitan. He concluded

that the algae act as framebuilders and, along with cement, as binders, and he described the Capitan as an organic reef.

Yurewicz (1976, 1977) worked the lower and middle Capitan (Fig 3.2). He found the Capitan to be composed of peloidal skeletal packstones and boundstones containing marine cement with the amount of boundstone increasing upward in the section. He proposed that the reef was composed of a diverse assemblage containing many suspension feeders that required hard substrate, adequate nutrients, and water of low turbidity. He noted that the reef was capable of wave resistance, but believed that it never was emergent. Using trigonometric techniques and the present dip of shelf deposits nearest the reef, he estimated reef depth to be 30 m at the upper shelfward edge extending down to 200 m at the basinward edge (Yurewicz, 1977, p. 85).

Neese and Schwartz (1977) worked in Walnut and Rattlesnake Canyons, respectively (Fig. 3.1). They studied the upper Yates and lower Tansill formations, divided these formations into three major carbonate units, and, within this stratigraphic interval, documented nine facies types. They confirmed that the facies tracts continuously parallel the shelf edge, but that they change rapidly perpendicular to the shelf edge. They also noted that shelf beds pinched out laterally at the shelf margin, and they documented the presence of subaerial erosional surfaces, including truncated tepees.

Hurley (1978; 1989) studied the Seven Rivers Formation in North McKittrick Canyon, defining eight shelf facies tracts along the Dog Canyon escarpment (Fig. 3.1). He found evidence (*viz.* geopetal structures) that the shelf beds nearest the Capitan ("fall in beds") had a primary seaward dip of 5-15°. Hurley's description of the "fall in beds" remains the strongest

evidence in support of Achauer and Dunham's marginal mound model.

Geologic Setting

The Capitan Formation and Carlsbad Group (Fig. 3.2) were deposited around the margin of the Delaware Basin during Late Permian time. At that time the relatively small (100 km diameter, 600 m deep (Harms, 1974)) Delaware basin was located a few degrees south of the equator on the western side of the continent of Pangea (Scotese et al., 1979). Formed as a result of tectonic down-warping on the southern margin of the North American plate, it was a cratonic basin, almost entirely surrounded by land (Harms, 1974; Ward et al., 1986). The dominant wind-direction in this equatorial area was probably from the east (Press and Siever, 1986). The ancestral Appalachian Mountains, located to the east and southeast of the Delaware Basin area (Scotese et al., 1979), may have influenced climatic conditions possibly acting as a rain shadow and contributing to desert conditions in the study during Permian time.

The presence of large evaporite deposits in the Delaware Basin and in its fringing lagoons indicates that climate during Late Permian time was arid. Extensive evaporitic lagoons (320 km wide) surrounded much of the basin during Guadalupian time (Adams and Rhodes, 1960; Harms, 1974) and evaporites filled the basin in Ochoan time (Hayes, 1964).

Evidence suggests that the water mass within the Delaware Basin was stratified with respect to oxygen content and that benthonic organisms were restricted to a zone around the basin margin. A narrow aerobic zone with a distinct biota including echinoderms and terebratulid brachiopods rimmed the immediate forereef (L. Babcock, 1977). Basinward, a zone 12-25 km (5-10 mi) wide contains a biota similar to that of modern

oxygen-deficient environments including siliceous sponges, protobranch bivalves, holothurians, ostracodes, textularid foraminifera, and soft-bodied burrowers (L. Babcock, 1974; see also Rhoades and Morse, 1971). The basinal rocks have high organic matter content for carbonates (0.10% to 1.76% by weight; Newell et al., 1953, p. 207). In addition, they are dark, laminated and contain few fossils or traces of benthonic organisms. The evidence strongly suggests that bottom waters were poorly oxygenated (L. Babcock, 1974) and possibly hypersaline.

The lack of oxygen in deep-basin waters was probably related to a combination of both salinity and temperature stratification (L. Babcock, 1974). Modern equatorial basins generally have a consistent surface water temperature year round. Annual overturn does not take place, and distinct thermal stratification is maintained. Because of the equatorial location of the Delaware Basin during Permian time, it is likely to have been stratified with respect to both salinity and temperature (D.W. Kirkland, personal communication, 1991). The basinward displacement of dense, saline (and/or chilled) waters that formed in shelf lagoons of the Delaware Basin has been suggested as the mechanism for deposition of basinal sands (Harms, 1974). These cool, dense, saline waters may have subsequently been trapped in the bottom of the basin, and would have undoubtedly contributed to salinity stratification and poor oxygenation of basinal waters.

The arid conditions during Permian time in the Delaware Basin resulted, indirectly, in the preservation of the Guadalupian Capitan complex. The basin and shelf deposits were encased in, and sealed by, Ochoan evaporites. The Delaware basin was initially filled by the evaporites of the Castile Formation and immediately afterward the

remaining basin, and much of the adjacent shelf, was filled, and covered, by the Salado Formation (Hayes, 1964, p. 16). Uplift began in the Pliocene epoch and continued through the last disturbance in the late Pleistocene (King, 1948) when erosion and the Pecos River system began to give the region its present geomorphic form (Thomas, 1972).

Today the Guadalupe Mountains are part of a large block, tilted 1-2° NE (Hayes and Koogle, 1958) and trending N36°E (Lang, 1937), which extends for approximately 80 km (50 mi) (Fig. 3.1). The Capitan Formation crops out at the south end of the range at Guadalupe Peak (2,666 m / 8,749 ft). From that point northward the range gradually looses elevation. The Capitan Formation forms an escarpment facing east along much of the range. North of Rattlesnake Canyon, however, the Capitan forms gentle, rounded hills and continues to loose elevation until it plunges into the subsurface near Carlsbad, New Mexico. Formations of the Carlsbad Group, made up of shelf facies associated with the Capitan Reef (Fig. 3.2), are exposed in a wide band (up to 7.5 km / 12 mi) to the northwest of the reef. The Capitan Formation and Carlsbad Group continue in the subsurface to the north and east around the margin of the Permian Delaware basin, where zones within the Carlsbad Group produce hydrocarbons (Fig. 3.3).

Methods

This study is based largely on field observations made in the field during one five-week session in 1988 and eight shorter sessions during 1987-1991. Permits were obtained prior to collection of samples within Carlsbad Caverns National Park and Guadalupe Mountains National Park. Localities studied in detail are illustrated on Figure 3.5 and described from

north to south in the following paragraphs.

Dark Canyon is the northern-most canyon along the block that forms the Guadalupe Mountains. The area studied was along the north wall near the mouth of the canyon. Samples of the Capitan and Tansill formations were taken along four short vertical traverses (average traverse spacing 104 m / 340 ft) and along one long horizontal traverse, which extended from the mouth of the canyon 380 m / 1250 ft to the west.

The most thorough petrologic study was done on samples of the Capitan and Tansill formations from Walnut Canyon (See Appendix B). On the southern wall of the canyon near the mouth, the transition between the reef and back reef was mapped in detail. In this area, samples were taken along one horizontal and four closely spaced (average 15.3 / 50 ft) vertical traverses. Two localities within the canyon and two localities along the escarpment to the south between Walnut and Rattlesnake Canyons also were studied in detail.

In Rattlesnake Canyon, one section encompassing the Capitan and Yates formations was measured. Another horizontal traverse from the Capitan Formation to Tansill Formation pisoids was made just to the north of Rattlesnake Canyon.

In Slaughter Canyon, outcrop quality was poor, and it was difficult to find an adequately exposed section. One section encompassing both the Capitan Formation and the Seven Rivers Formation was measured. This section is located between section one of Yurewicz (1976) and section eight of Hayes and Koogle (1958).

The "Permian Reef Geology Trail" in McKittrick Canyon provided the best exposures of the Capitan Formation (Yates equivalent).

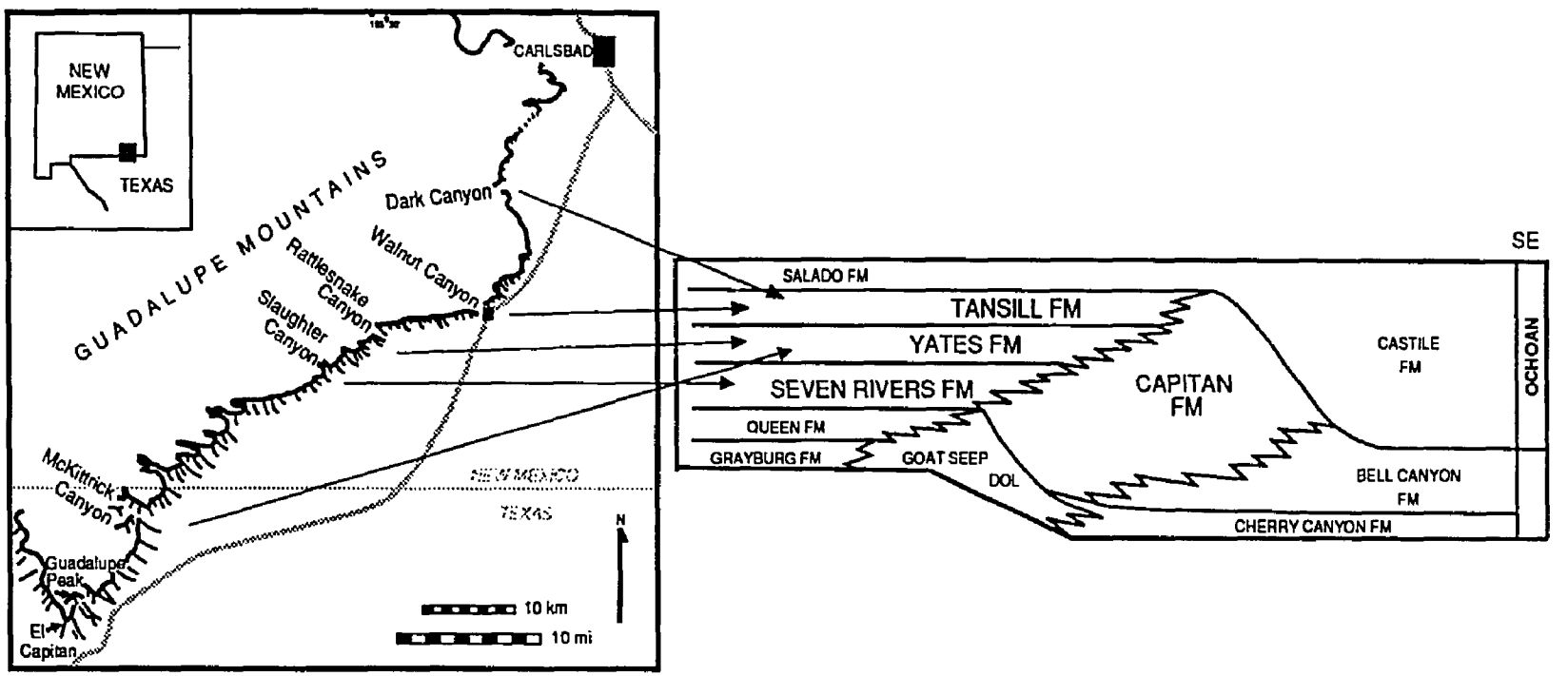


Figure 3.5. Locations of accessible exposures for each portion of the sections studied.

Many observations about fossil types, lithology, and rock fabric in the Capitan Formation were made from the extensive exposures along this trail, which was constructed between 1980 and 1984 (V. Davila, personal communication, 1991). In addition, observations made on samples prepared at Texaco Exploration and Production Technology Division for a reef-trail guidebook to be published at the Bureau of Economic Geology (Bebout et al., in preparation) have been incorporated into this discussion.

Whenever possible, sample localities were marked precisely on topographic maps or on enlarged photographs. Samples were taken every 3 m / 10 ft along most measured sections and traverses. Each sample taken was slabbed, inspected, and thin sectioned if appropriate.

CAPITAN FORMATION: COMPARISON TO A MODERN REEF

The Capitan Formation is similar to a modern framework reef in many respects. The formation contains a diverse array of organisms, including both framebuilders and binders. It also exhibits internal sediment, intra-frame geopetal structures, and abundant marine cement. On a larger scale, erosion reveals geomorphic features in the Capitan that are identical to the buttress-channel morphology characteristic of present day fore-reef zones. Each of these aspects will be discussed.

Capitan Formation Biota—Observations

Perhaps the most striking feature about the Capitan in outcrop is the diversity of the biota. Species diversity within the reef (approximately 350 taxa) has been described as "truly enormous" (Fagerstrom, 1987). The most abundant organisms are: calcareous sponges, bryozoans, the putative calcareous alga, *Archeolithoporella,* and an organism of uncertain affinity,

Tubiphytes. Other types of organisms include: siliceous sponges, brachiopods, corals, foraminifera, trilobites, bivalves, gastropods, crinoids, scaphopods, cephalopods, *Colenella, Eugonophyllum,* and other problematic organisms (Girty, 1908; Johnson, 1942; King, 1948; Newell et al., 1953; J. Babcock, 1974; 1977; Yurewicz, 1976, 1977; Toomey and Babcock, 1983; Babcock and Yurewicz, 1989). This is considered to be a normal marine biota (Babcock and Yurewicz, 1989), based on the high diversity of the assemblage and on the presence of fossils whose modern descendants are intolerant to large variations of salinity and are today found in waters of normal marine salinity.

Capitan Framebuilders—Observations

Sponges dominate the Capitan Formation (Fig. 3.6). They are calcareous sponges, dominantly Sphinctozoas (Thalamida) with minor Inozoans (Pharentronida). *Ambylsiphonella, Cystauletes, Cystothalmia,* and *Guadalupia* are among the most common fossil calcareous sponges (Yurewicz, 1976). In thin section these sponges are replaced by a sparry calcite mosaic suggesting that they were originally aragonitic. Similar calcareous sponges are still found in modern reefs, where they are forced into deep water or caves by more efficient, light-dependant organisms (Wood, 1990) (Fig. 3.7). Calcareous sponges are capable of creating reef framework (Hartman and Goreau, 1970; Land and Moore, 1980). Siliceous sponges are also present in the Capitan, but they are more abundant in the lower portion of the formation (Babcock and Yurewicz, 1989).

Sponges are potentially significant to any paleoecologic reconstruction of the Capitan reef. In general, Holocene sponges of the

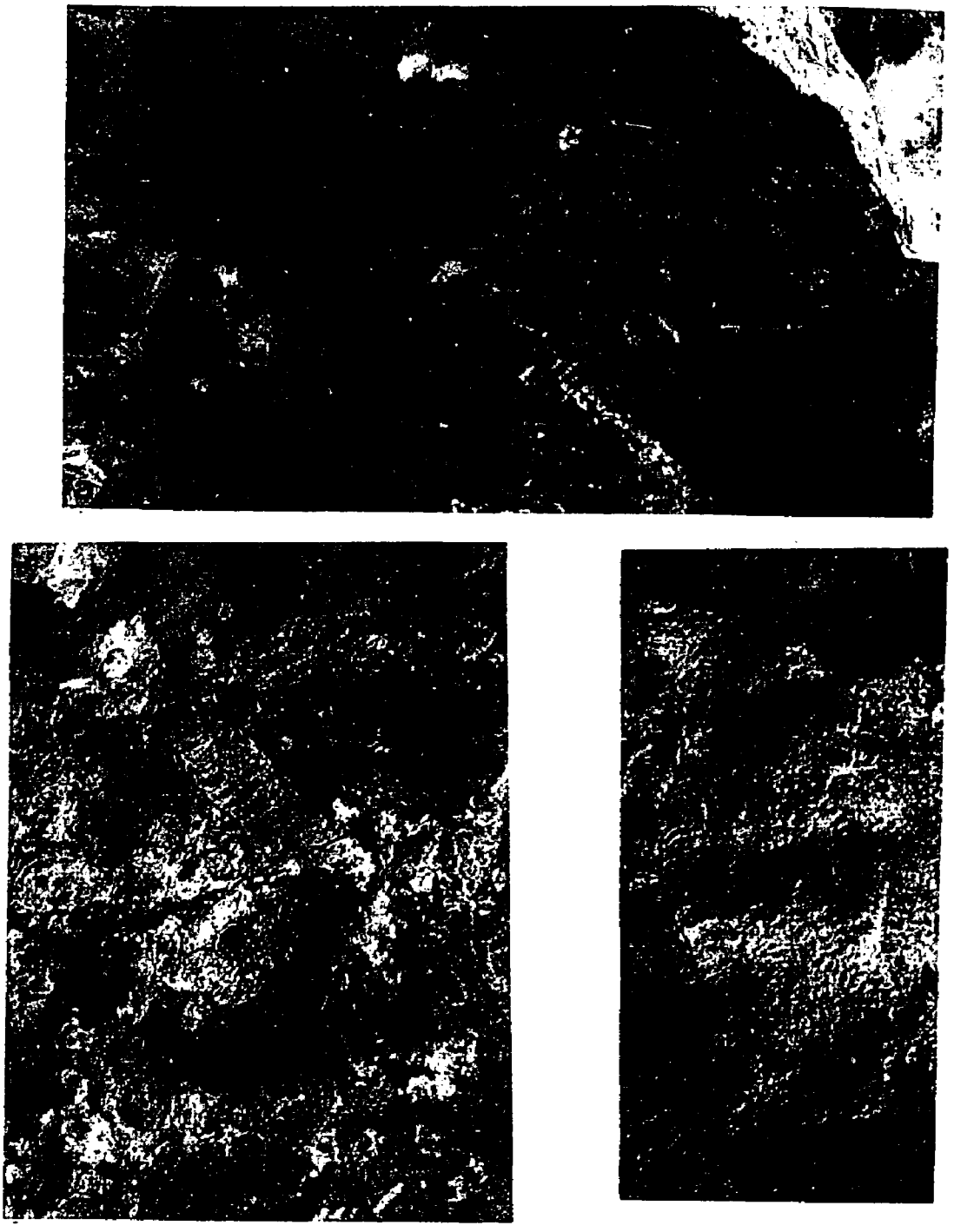


Figure 3.6. Capitan Formation fossil sponges. (a) Capitan Formation outcrop showing tremendous diversity among sponges, at least five different types are preserved on this surface. (b) The sponge *Amblysiphonella*. (c) The sponge *Guadalupia*.

class Calcarea (calcareous sponges) are most common at depths of less than 100 m, whereas Holocene sponges of the class Hexactinellida (siliceous sponges) are most common in the depth range of 200-300 m (Raup and Stanley, 1971). A similar relationship apparently held true in the Permian. Finks (1960, p. 9) in his study of siliceous sponges from the Permian of West Texas, suggested that calcareous sponges required shallow, warm conditions to flourish. He apparently based his conclusions on the lack of calcisponges in adjacent deep water facies.

The role of sponges as framebuilders in the Capitan reef is not directly analogous to the role of scleractinian coral in a modern reef. Sphinctozoan sponges were not heavily calcified. They were, however, densely packed, and combined with abundant binding organisms, were probably capable of creating a rigid, wave-resistant framework (Fagerstrom, 1987, p. 386). In the Capitan Formation the percentage of boundstone increases up section from 5-20% in the lower Capitan, to 20-60% in the middle Capitan, and to 50-75% in the upper Capitan (Babcock and Yurewicz, 1989). In comparison, cores from a modern Caribbean reef probably contain less than 20% framework. Although these cores contain an average of 41% solid material, over half of this solid material is detrital in nature (Hubbard, 1989).

Capitan Binders

Organisms of the Capitan Formation that encrusted, and potentially acted as binders, include algae, bryozoans, and organisms of uncertain affinities. Among these fossils, probably the most important volumetrically is the red alga *Archeolithoporella* Endo 1959 (Fig. 3.8). *Archeolithoporella* is present throughout the Capitan Formation, although

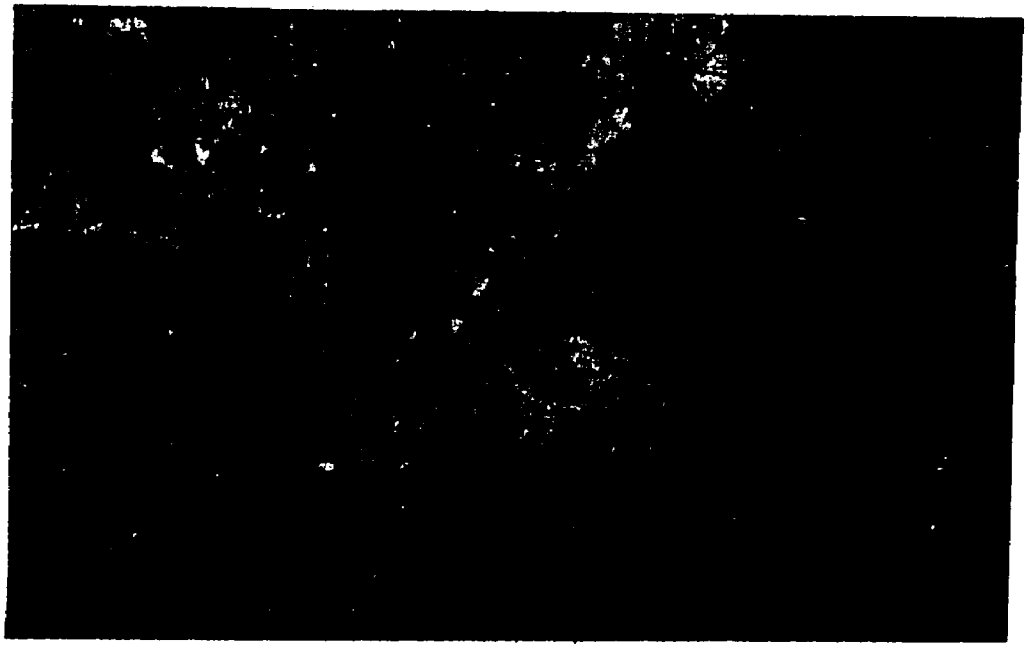


Figure 3.7. Calcareous sponge framework, Jamaican forereef 90 m. Photo by W. D. Hartman.

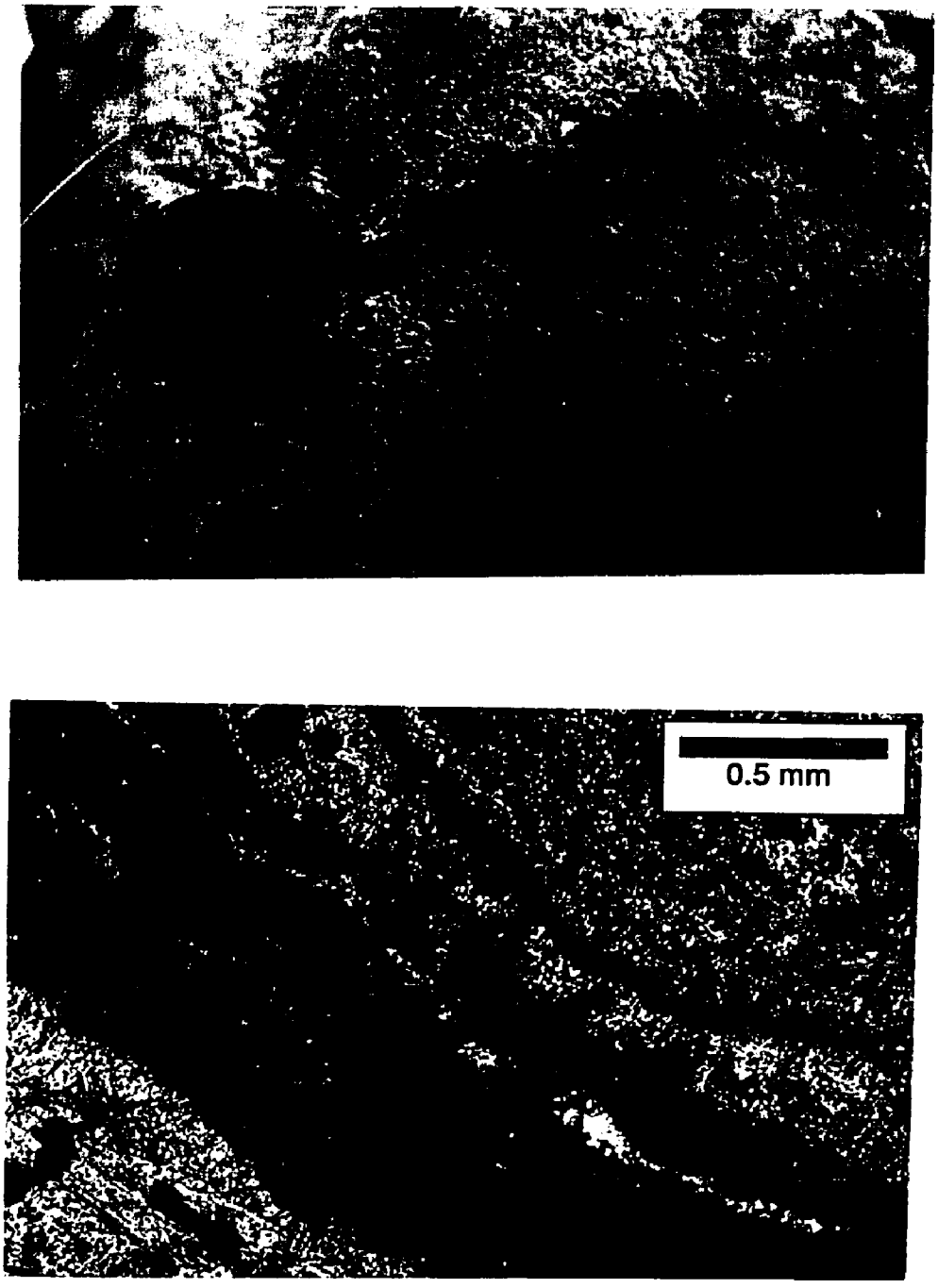


Figure 3.8. *Archeolithoporella* (a) on outcrop (b) in thin section.

calcareous algae in general are relatively more abundant in the upper Capitan (Babcock and Yurewicz, 1989). *Archeolithoporella* boundstone is particularly well exposed in the middle Capitan Formation along the McKittrick Canyon Reef Trail and in large areas (> $1m^2$) in the Left Hand Tunnel in Carlsbad Caverns. *Archeolithoporella* boundstone is found as thin, concentric, micritic layers around a skeletal substrate and as micritic layers interlaminated with fibrous cement (Yurewicz, 1976, 1977; J. J. Babcock, 1974; 1977). The cement is commonly replaced by a sparry mosaic suggesting an original aragonitic composition. Based largely on the presence of interlaminated, previously aragonitic cement *Archeolithoporella* is tentatively classified with the red algal family Peyssonneliaceae/Squamariaceae (J. Babcock, 1974; James et al., 1988).

The organism *Tubiphytes* is a volumetrically significant binder of problematic affinities (Fig. 3.9). Present throughout the Capitan, it is visible in outcrop as small porcelaneous encrusting or erect tube-like forms. It seems ubiquitous, appearing in most thin sections as encrustations on other organisms, individual branches or clumps of branches, or as broken, angular to subangular micritic fragments.

Capitan Internal Sediment

In addition to framebuilders and binders, the massive member of the Capitan Formation contains large amounts of internal sediment (Fig. 3.10). Internal sediment in a modern reef, deposited between and within reef framework, is derived from multiple sources. The coarse traction-load of reef-derived sediment moving down slope is caught in the framework. In addition, a portion of the suspended load – silt and mud sized particles of

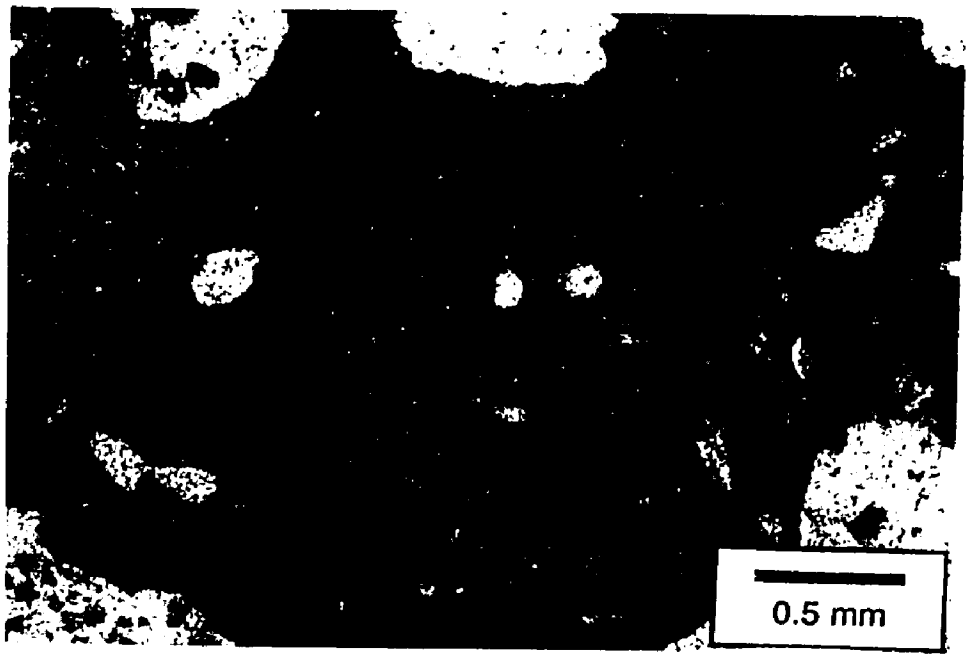


Figure 3.9. Thin section photomicrograph of *Tubiphytes*.

$CaCO_3$ – is baffled by the framework and deposited. Additional components of internal sediment are clay-sized crystals of inorganically precipitated $CaCO_3$. In a modern reef, internal sediment is often deposited as geopetal fill of framework voids, then it is cemented, and bored. These borings may be refilled with internal sediment, cemented, and bored again and again. The internal sediment is not a rock type, *sensu strictu*, but is instead part of the framestone or bindstone.

Internal sediment in the Capitan is similar to examples from a modern reef (Fig. 3.11). Extraordinary surfaces along the McKittrick Canyon Reef Trail show laminated, frequently tilted, geopetal infill of framework porosity (Fig. 3.10). Components visible in thin section of internal sediment include: subangular micritic grains, round micritic grains ranging in size from 15 μm to 0.5 mm (probably including peloidal cement, pellets, and peloids), ostracods, possible sponge spicules, trilobite fragments, foraminifera, mollusc fragments, bivalve fragments, echinoderm fragments, and abundant sub-angular to rounded, micrite-rimmed grains, whose original aragonitic structure is replaced by sparry calcite. Peloids are more common in the lower Capitan (Yurewicz, 1976), and bioclastic material is more common in the upper Capitan (J. Babcock, 1974).

Multiple episodes of boring and infill were not observed in thin sections of internal sediment from the Capitan Formation. In modern internal sediment disinctively-shaped, 40 μm chips produced by clionid sponges are common. Allochems similar to clionid chips were not found in the Capitan Formation.

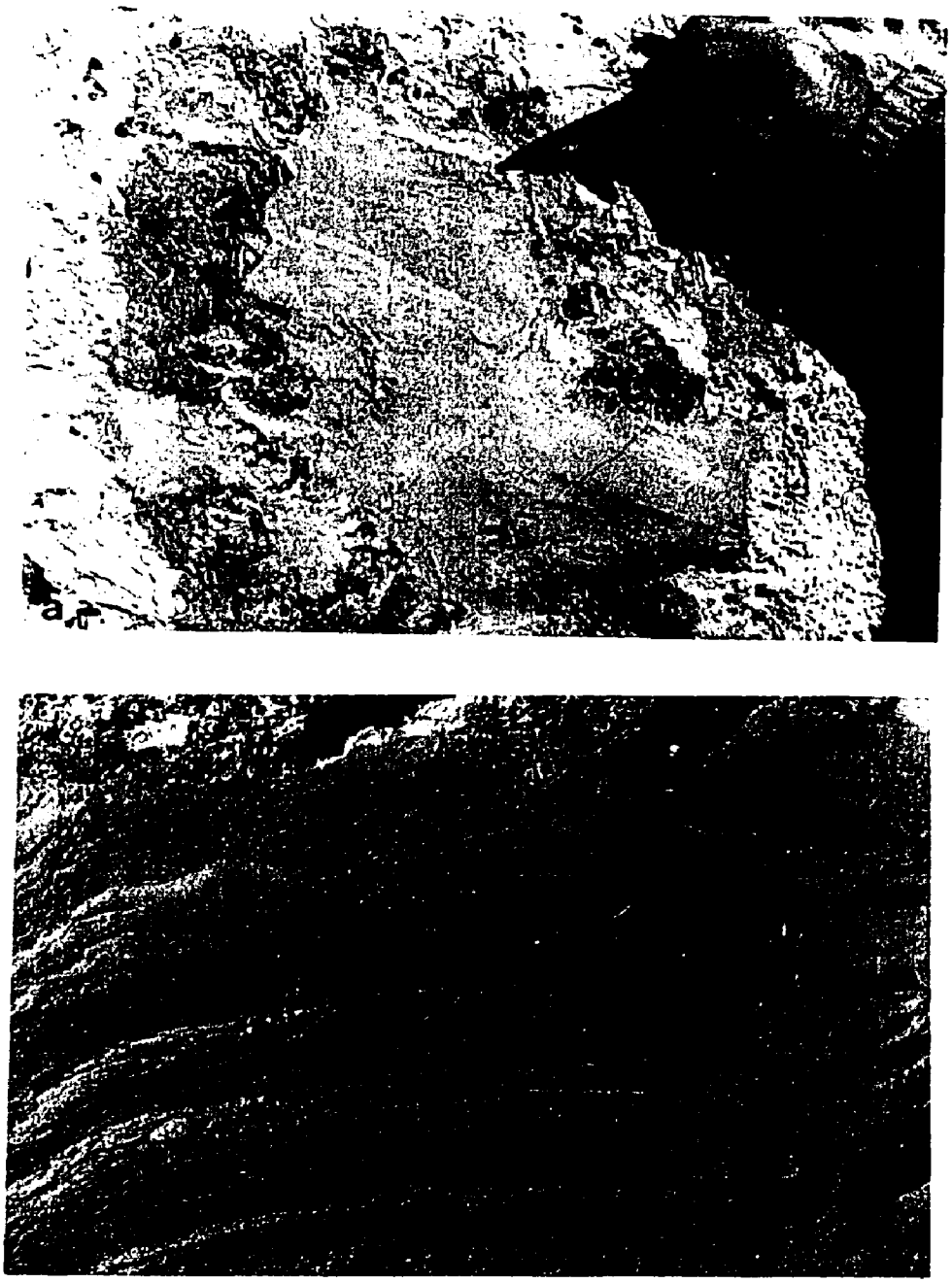


Figure 3.10. (a) Internal sediment filling a framework void. (b) Close up of internal sediment in another locality. Both photographs were taken along the Permian Reef Geology Trail in McKittrick Canyon.

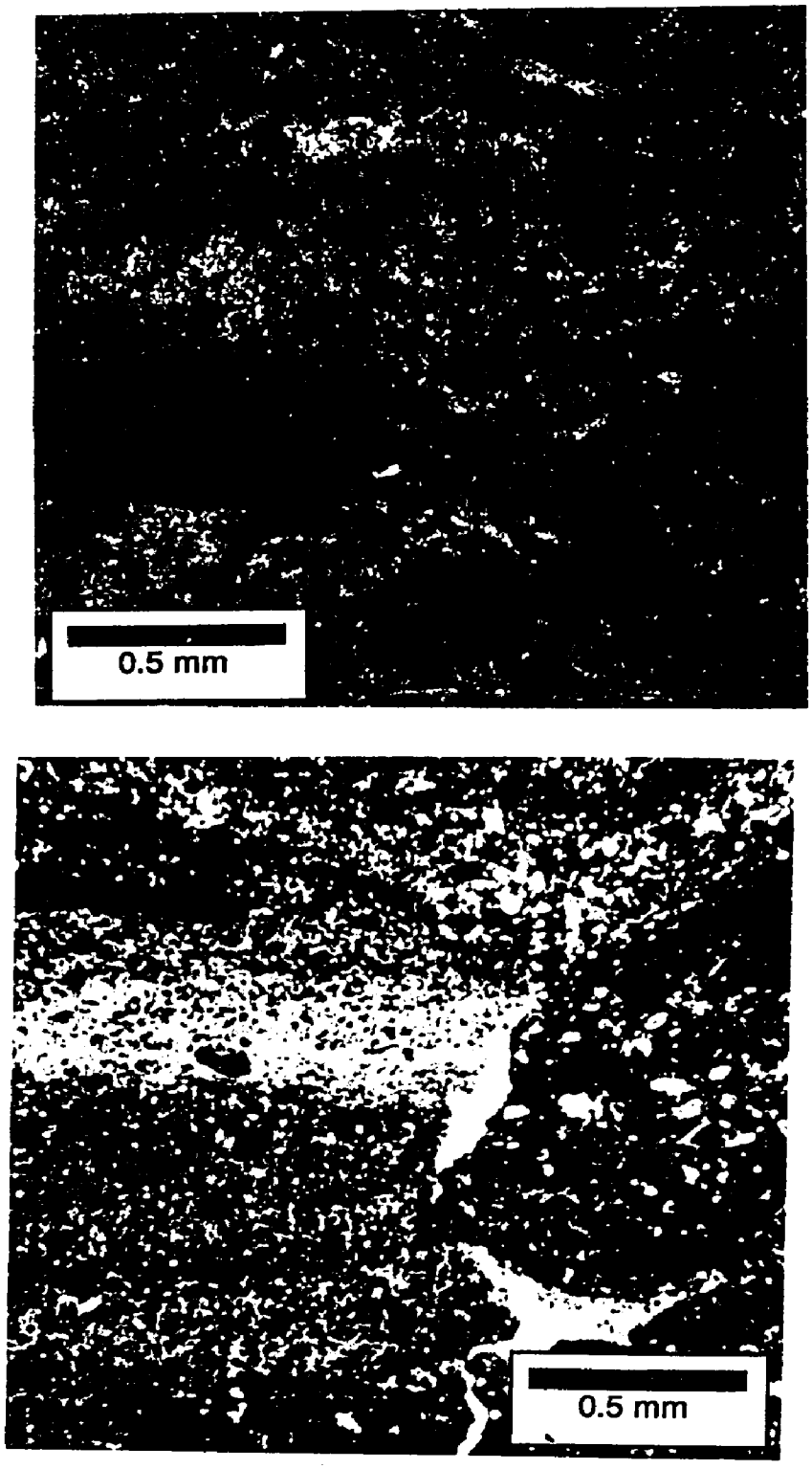


Figure 3.11. Internal sediment in the Capitan Formation (a) and from a modern Jamaican reef (b).

Capitan Marine Cement

Botryoidal Aragonite

The Capitan Formation contains prodigious amounts of cement thought to have been precipitated in the marine environment. Cement described as "radial fibrous botryoidal cement" (J. Babcock, 1974; Mruk, 1985; 1989) is found as radial fans 1-3 cm across (Fig. 3.12 a, b). These radial fans fill framework voids (0.5 m in diameter). In thin section it is apparent that these botryoids are replaced by a sparry calcite mosaic. The botryoids are composed of crystals that originally had square-tipped shapes (Fig. 3.12 b) (Loucks and Folk, 1976), and still retain a relatively high Sr content (up to 559 ppm). Based on observations in outcrop, petrographic, and geochemical data, this "radial fibrous botryoidal cement" is thought to be an aragonitic marine cement. It is morphologically identical to botryoidal aragonite in modern reefs.

Three lines of evidence suggest that at least part of this previously aragonitic cement was precipitated contemporaneously with active reef-growth. First, aragonitic cement is interlaminated with the organism *Archeolithoporella*. Second, in some thin sections, reef-derived sediment is deposited on top of botryoids. And third, in one thin section previously aragonitic botryoids large (1-2 mm) scallops along one margin suggesting abrasion by an unknown bioeroding organism.

The vertical distribution of aragonitic cement in the Capitan, when compared to modern reefs, raises questions about the chemistry of Permian sea water and the depth of Capitan reef growth. Aragonitic cement is present in the lower Capitan, but the volume of aragonitic cement increases in the middle and upper Capitan (Yurewicz, 1987). Although not as abundant as originally aragonitic cement in the Capitan, aragonitic

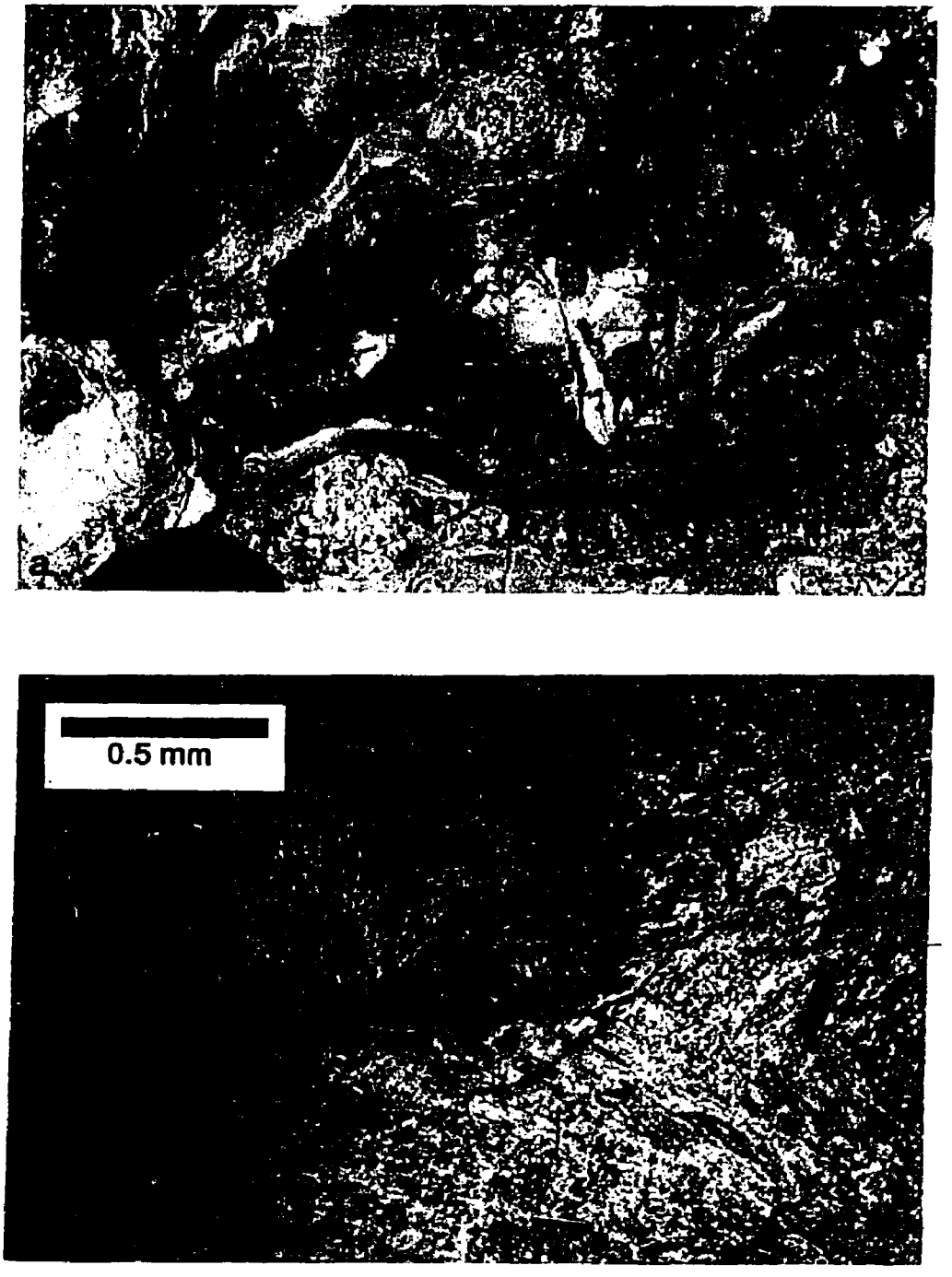


Figure 3.12. Botryoidal aragonite. (a) Outcrop photo (A). This is the initial infill of a reef framework void. (b) Thin section photomicrograph.

botryoidal cement is present in modern reefs. In the Belize Barrier Reef, botryoidal aragonite is present as void filling massses as much as 5 cm thick along the vertical reef wall (65-125 m deep) (Ginsburg and James, 1976).

The lateral distribution of aragonite in the Capitan seems to be significant to a model of the paleomorphology of the shelf. Although original aragonitic cement is abundant in the Capitan shelf margin reef framework, it is absent in sediments just shelfward of the reef. This is directly analogous to the pattern of cementation in a Holocene reef from the southeast Florida shelf. In this modern example, marine cementation is high in the shallow, windward (basinward) side of the reef and marine cementation is low in the leeward (shelfward) side of the reef. The abundance of marine cement in the upper windward zone of this Holocene reef is attributed to relatively high energy level and relatively low sediment-accumulation rate (Shinn, 1969; Lighty, 1985; Moore, 1989). The similar distribution of cement suggests that the Capitan reef also existed in conditions of relatively high energy and low sediment accumulation. The high-energy conditions may have been due to wave pumping and the low rate of sediment accumulation may have been due to transport of sediment downslope.

Radiaxial Calcite

A second type of cement, thought to be precipitated in the marine environment, is abundant in the Capitan Formation. This cement is described as "isopachous fibrous radiaxial cement" and as "prismatic cement" (Mruk, 1985). It has, however, distinct characteristics of cements described as "radiaxial" (Fig. 3.13). The term "radiaxial" is used in

reference to a calcite crystal composed of subcrystals whose C-axes, and points of extinction, are different than that of the main crystal. The term radiaxial can be more rigorously defined as "the peculiar combination of curved twins, convergent optic axes, and diverging subcrystals, *within* a cement crystal" (Bathurst, 1975, p. 426). The Capitan cements exhibit all the above characteristics except that no curved twins were found. Some of the cements described here as "radiaxial" actually include fasicular optic calcite. Fasicular optic calcite is distinguished by the presence of a divergent pattern of fast-vibration directions. This pattern coincides with that of the subcrystals (Kendall, 1985, p. 59).

Radiaxial cements in the Capitan formed after aragonite precipitation, after creation of scalloped borings, after growth of *Archeolithoporella,* and after deposition of internal sediment. Therefore, radiaxial cements are considered to have formed after active reef growth. Radiaxial cements are more abundant in the lower portion of the Capitan (Yurewicz, 1978) and, unlike aragonite, are also present in sediments deposited just shelfward of the reef.

Radiaxial cement was previously thought to be a replacement of earlier acicular bundles, but was found being actively precipitated into voids in the marine phreatic environment in Enewetak Atoll in the Pacific (Kendall, 1985; Saller, 1986). Radiaxial calcite from the Capitan Formation is strikingly similar to the radiaxial calcite described by Saller (1986) from Enewetak. At Enewetak radiaxial calcite is hosted by lower Miocene strata (377-819 m deep) and is presently forming in open communication with Holocene Pacific ocean water that is undersaturated with respect to aragonite (that is, it is below the aragonite lysocline). The driving mechanism for the formation of the Enewetak radiaxial calcite

Figure 3.13. Fasicular optic calcite (similar to radiaxial calcite) from the Capitan Formation.

cement is marine water movement through the atoll by thermal convection (Saller, 1986). Radiaxial cements found in the Capitan Formation are also considered to be marine, and based on diagenetic distribution patterns, they probably formed under similar conditions.

Capitan Geomorphic Features

The Capitan is divided into two members — the massive member and the breccia member — which can be distinguished by their appearance in outcrop, especially when viewed from a distance (King, 1948; Hayes, 1964). In McKittrick Canyon, for example, the massive member of the Capitan forms impressive cliffs, whereas the breccia member forms "ragged" slopes (Hayes, 1964) with slightly denser, though not homogeneous, vegetation. The breccia member is composed of vague, thick beds dipping 20-30° southeastward (basinward). The massive and breccia members of the Capitan Formation have been interpreted as reef and forereef, respectively (Lloyd, 1929; Cys, 1971).

The eastern escarpment of the Guadalupe Mountains between Walnut and Rattlesnake Canyons exhibits striking ridge and gully topography (Fig. 3.14). The ridges are oriented perpendicular to the trend of the escarpment (N15°E). This topography may be clearly seen on topographic maps (Fig. 3.15). It has been suggested that these ridges represent relict spur and groove structures (Schmidt, 1977).

Inspection of outcrops along the ridges between Walnut and Rattlesnake Canyons reveals *in situ* framework reef. The intervening gullies contain carbonate sands (reef-derived allochems) with festoon cross-bedding (Fig. 3.14). This pattern of ridges of *in situ* framework reef (spurs or buttresses) and channels filled with cross-bedded carbonate sand

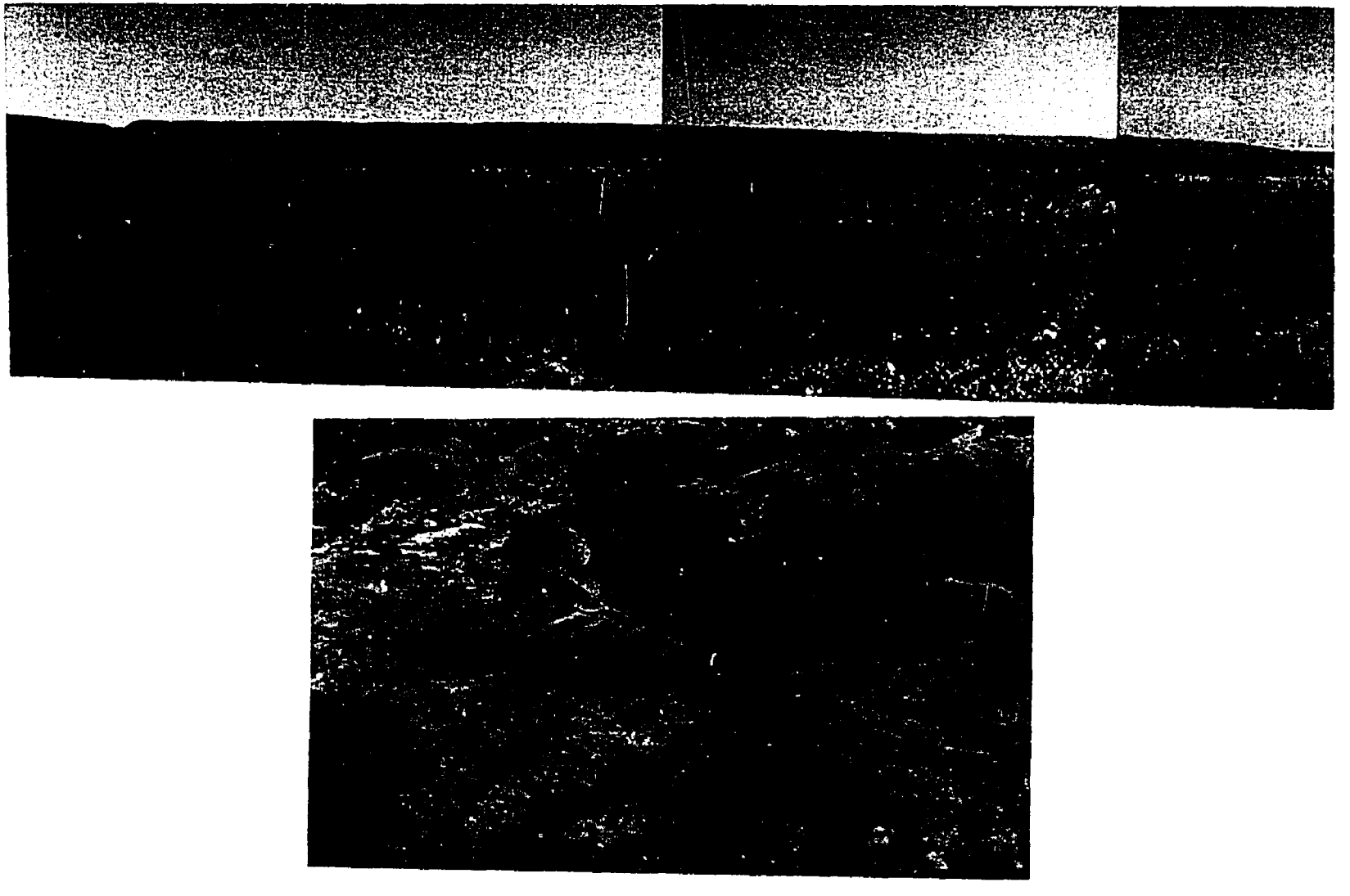


Figure 3.14. (a) Photograph of escarpment between Walnut and Rattlesnake Canyons. (b) Bedforms in groove structure.

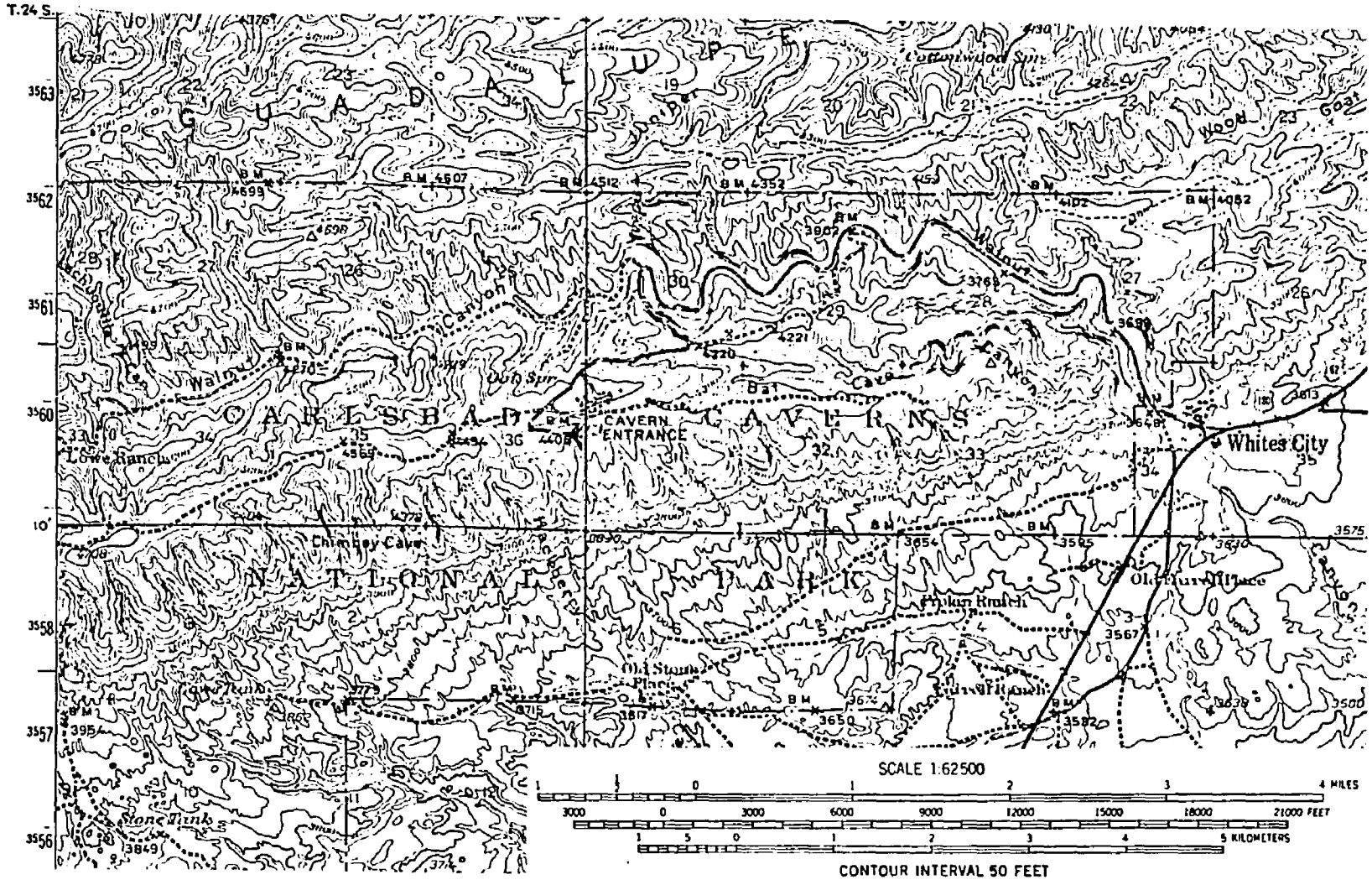


Figure 3.15. Map of the escarpment near Walnut Canyon showing ridge and gully topography.

(grooves) is identical to the seaward topography of modern reefs. The combination of lithologic and topographic evidence suggests that the ridges between Walnut and Rattlesnake Canyons are slightly eroded, relict features reflecting Permian submarine topography. Preservation of these features is possible because they were encased in evaporites soon after deposition and have been exhumed only recently.

Modern canyons in the Guadalupe Mountains may have formed at the sites of Permian paleocanyons, as suggested by tongues of the Bell Canyon Formation that are found within McKittrick Canyon (Schmidt, 1977). Silver and Todd (1969) also proposed that submarine canyons were cut through shelf-margin strata as conduits for siliciclastic basin-fill, but they did not provide clear evidence.

Circumstantial evidence for a submarine channel is present within, and just south of, Walnut Canyon. High-energy grainstones and packstones are found 0.3 km (0.2 mi) shelfward (to the west) of the reef in Walnut Canyon. Lithologies suggesting lower depositional energy, packstones and wackestones containing articulated dasyclads, are present along the escarpment south of Walnut Canyon, less than 0.16 km (0.1 mi) shelfward (to the west) of the reef (Fig. 3.16). In addition, herringbone crossbedding (crossbedding dipping alternately basinward and shelfward) is seen along many canyon walls, but has not been found along the escarpment. This suggests that the tidal currents may have been active in the channels.

Harwood (1989) described a channel (230 m wide) filled with large, angular, rotated reef-blocks in a matrix of reef-derived sand from the Left Hand Tunnel of Carlsbad Caverns. *In situ* reef is present on either side of the channel. This study suggests that the channel was filled by a series of

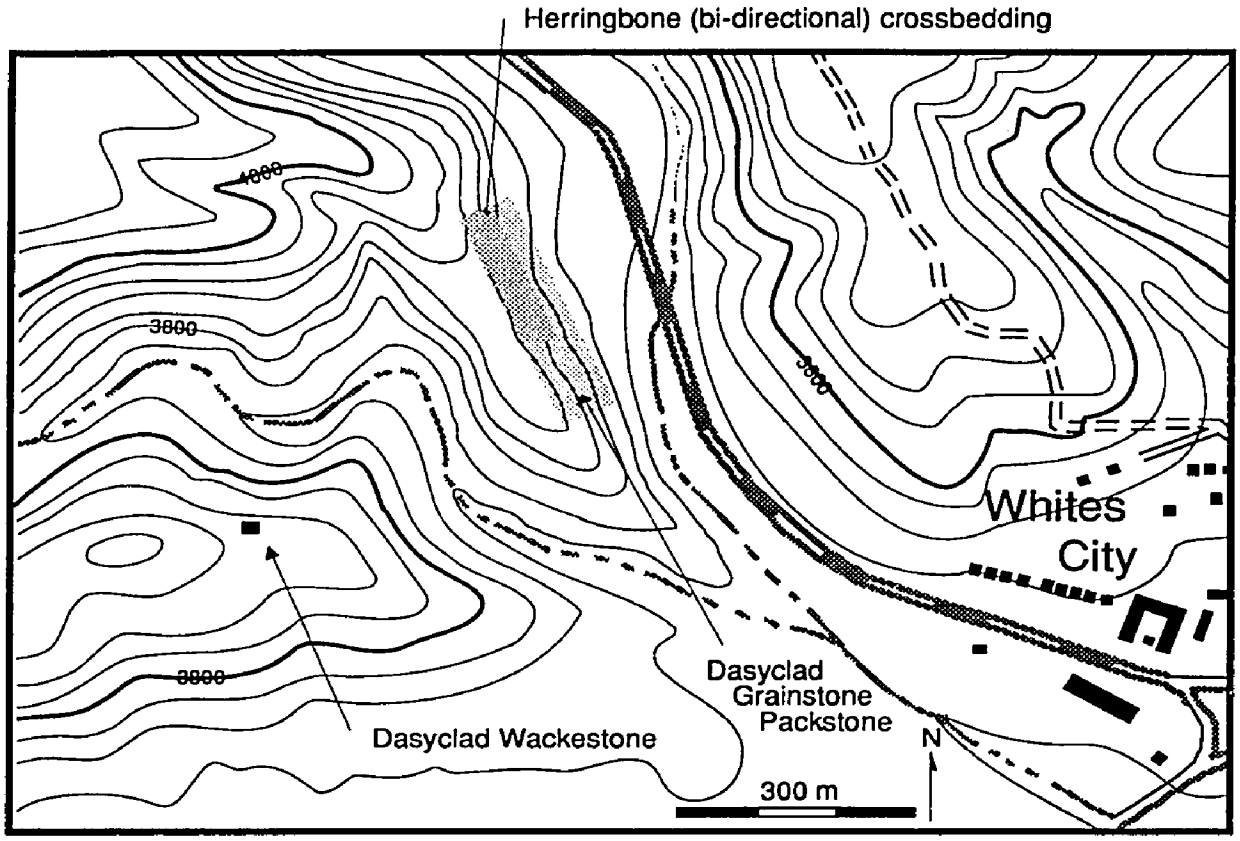


Figure 3.16. Map of Walnut Canyon showing relative locations of grainstone, packstone, and wackestone.

block- and sand-rich sequences. The sharp, angular boundaries of the blocks suggest that they were lithified prior to breakage and redeposition (Fig. 3.17).

Capitan Formation—summary and discussion

The Capitan was formed by a diverse, open marine biota. Calcareous sponges acted as framebuilders and calcareous algae and other organisms acted as binders. Internal sediment was deposited as geopetal fill in framework voids. Prodigious amounts of marine cement were precipitated in the reef. Aragonitic botryoidal fans were precipitated, at least initially, contemporaneously with reef growth. Analogous to modern settings, the locus of precipitation of marine cement was at the shelf margin. Isopachous rims of radiaxial calcite were deposited after reef growth and precipitation of aragonite, suggesting a fundamental change in pore water chemistry, probably related to water depth.

Large-scale features of the Capitan Formation are also significant. It is divided into a massive and a brecciated member analogous to the reef and forereef of modern systems. Relict spur and groove topography is preserved along a portion of the Guadalupe Mountains escarpment. Subtle, perhaps circumstantial, evidence for paleochannels is seen along present-day canyons. This evidence suggests that the Capitan reef, like a modern reef, was a chain of reefs separated by channels. Also like a modern reef, a series of regularly spaced spur and groove structures formed on the basinward side, and large and small angular blocks dislodged from the reef were deposited in the forereef below.

The description of the Capitan Formation suggests that it was remarkably similar in morphology and lithology to a modern reef. The

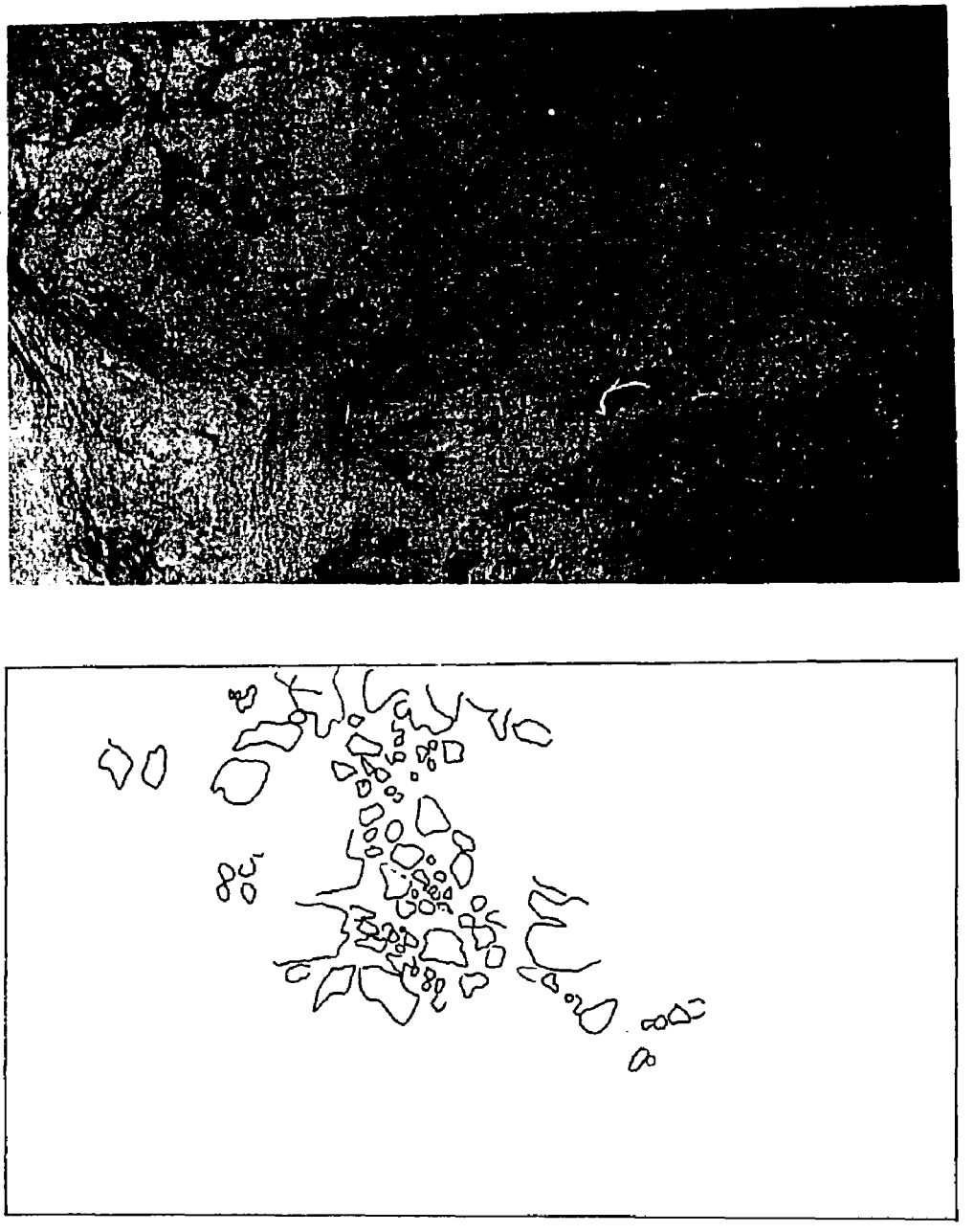


Figure 3.17. Reef breccia exposed in the ceiling of the Left Hand Tunnel of Carlsbad Caverns. Blocks are meters in diameter.

physical factors that controlled its development are those that control the development of modern reefs. Prolific accumulation of carbonate occurs at modern carbonate shelf margins because of a unique combination of factors. At the margin of a shelf or platform cold waters charged with carbon dioxide are warmed and agitated. This results in release of CO_2 from these cold waters and facilitates precipitation of $CaCO_3$. Waves and currents at the shelf margin provide a continuous supply of nutrients. The same currents that bring food in, carry wastes and sediment out. In modern reefs, photosynthetic organisms, as well as filter feeders, are dependant on clear, warm waters.

Evidence suggests that the Capitan reef formed in an environment where the same unique combination of factors occurred. The reef formed at the Delaware basin shelf margin. The prodigious amount of aragonitic cement suggests that at this shelf margin waters were primed for prolific precipitation of $CaCO_3$.

Based on the number and density of filterfeeding organisms in the Capitan reef it has been suggested that waves and currents brought in an ample supply of nutrients and plankton (L. Babcock, 1974). The same currents probably removed sediment as suggested by festoon crossbeds preserved within grooves on the Capitan escarpment south of Walnut Canyon.

Clarity of the Delaware Basin waters can perhaps be inferred from the abundance of filterfeeding organisms. The red and green algae preserved on the reef were also dependent on clear water. Curiously, some siliciclastic silt was found in a few thin sections of the reef facies suggesting some siliciclastic sedimentation was contemporaneous with reef growth.

Upon closer examination the Capitan Formation is lithologically

analogous to a modern reef. The Capitan framework is made up of sponges that played a role similar to the role of scleractinian corals in a modern reef. In the Capitan Formation, as in a modern reef, red algae, bryozoans, and foraminifera acted as binders. Internal sediment in the Capitan is almost identical to internal sediment in a modern reef. The clotted micrite fabrics, fragments of reef debris, and cemented zones in Capitan internal sediment lack only the distinctive clionid chips and multiple generations of borings typical of modern internal sediment.

The hypothesis that the Capitan Formation was deposited as a framework reef is not new. It has been described as an organic reef with potential for wave resistance (J. Babcock, 1974, 1977; Yurewicz, 1976, 1977). The suggestion that the reef grew to sea level and acted as a barrier to open ocean currents is not new either (Adams and Rhodes, 1960; Cronoble, 1974; Cys, 1971), but it is not widely accepted. The depth at which an ecosystem developed is difficult to establish. The estimate presented in the following paragraphs is based on analysis of the limiting factors that control biotic distribution and diversity in a modern reef.

Several factors suggest that the Capitan reef formed in shallow water. The most obvious limiting factor controlling the depth and diversity of modern reef growth is light, but dependence on light is difficult to determine for the Capitan reef. Although some modern sponges contain symbiotic algae (Bold and Wynne, 1985), it is probably impossible to establish their presence in Permian sponges. Modern algae analogous to those found in the Capitan are found at a wide range of depths.

Other limiting factors are less obvious, but potentially more important. Benthic fossil assemblages and dark, bedded basinal rocks

suggest that oxygen decreased with depth in the Delaware basin. In modern oxygen-poor basins diversity, particularly among calcified organisms, decreases markedly with depth (Rhoades and Morse, 1971). The diverse Capitan biota was probably restricted to the upper, oxygenated regions of the basin. The depth of oxygen restriction in the Delaware basin is difficult to establish, but would probably have been related to the depth of the thermocline and halocline. Depth of the thermocline is difficult to estimate, but it would have been below wave base or below currents that would cause mixing. Depth of the halocline is also difficult to estimate. The Cariaco Trench, a modern, equatorial, anoxic basin stratified with respect to oxygen, temperature, and salinity and seems to bear some similarity to the Delaware basin. In the Cariaco Trench stratification is related in large part to the depth of the sill (Richards, 1960). If the Delaware basin were a silled basin at Guadalupian time, the depth of that sill probably controlled salinity and possibly temperature stratification. Absolute depths are impossible to establish.

The information presented in this report thus far cannot be used to establish whether the reef flourished below wave base or grew to sea level. In the next section, evidence from the shelf sediments will support the inference that the reef grew to sea level.

FORMATIONS OF THE CARLSBAD GROUP: OUTER SHELF SEDIMENTATION

The previous section documented the characteristics of the Capitan Formation that suggest its deposition as a shelf margin framework reef with a capacity for wave resistance. In this section we will present evidence that this framework reef acted as an

efficient barrier to circulation of marine water. We will concentrate on the characteristics of the formations of the Carlsbad Group (in ascending order, the Seven Rivers, Yates and Tansill formations) and, in particular, those portions of these formations deposited closest to the reef, on the outer shelf.

The reef to shelf transition is marked by an abrupt change from massive reef boundstone, with a diverse biota, to bedded grainstone and packstone, with a biota indicative of hypersaline marine waters. The biotic content and the distribution of mud in the outer shelf facies is such that the sediments near the reef are bioclastic grainstones and packstones, while further shelfward the percentage of mud increases and peloid, dasycladacean algae, foraminifera packstone dominates. The transition to pisoid-bearing packstone and wackestone is gradational. These two lines of evidence suggest that the reef formed an abrupt barrier along the shelf margin and that a quiet lagoon existed across the outer shelf.

Shelf margin to outer shelf transition

The transition from the massive Capitan Formation to the bedded Tansill Formation was mapped in detail near the mouth of Walnut Canyon (Fig.3.18). In Walnut Canyon, this lateral transition between massive boundstone of the Capitan Formation and bedded sediment of the Tansill Formation is abrupt. Large *in situ* sponges, massive cements, and boundstone fabrics of the reef massive are abruptly transitional to bedded grainstones and

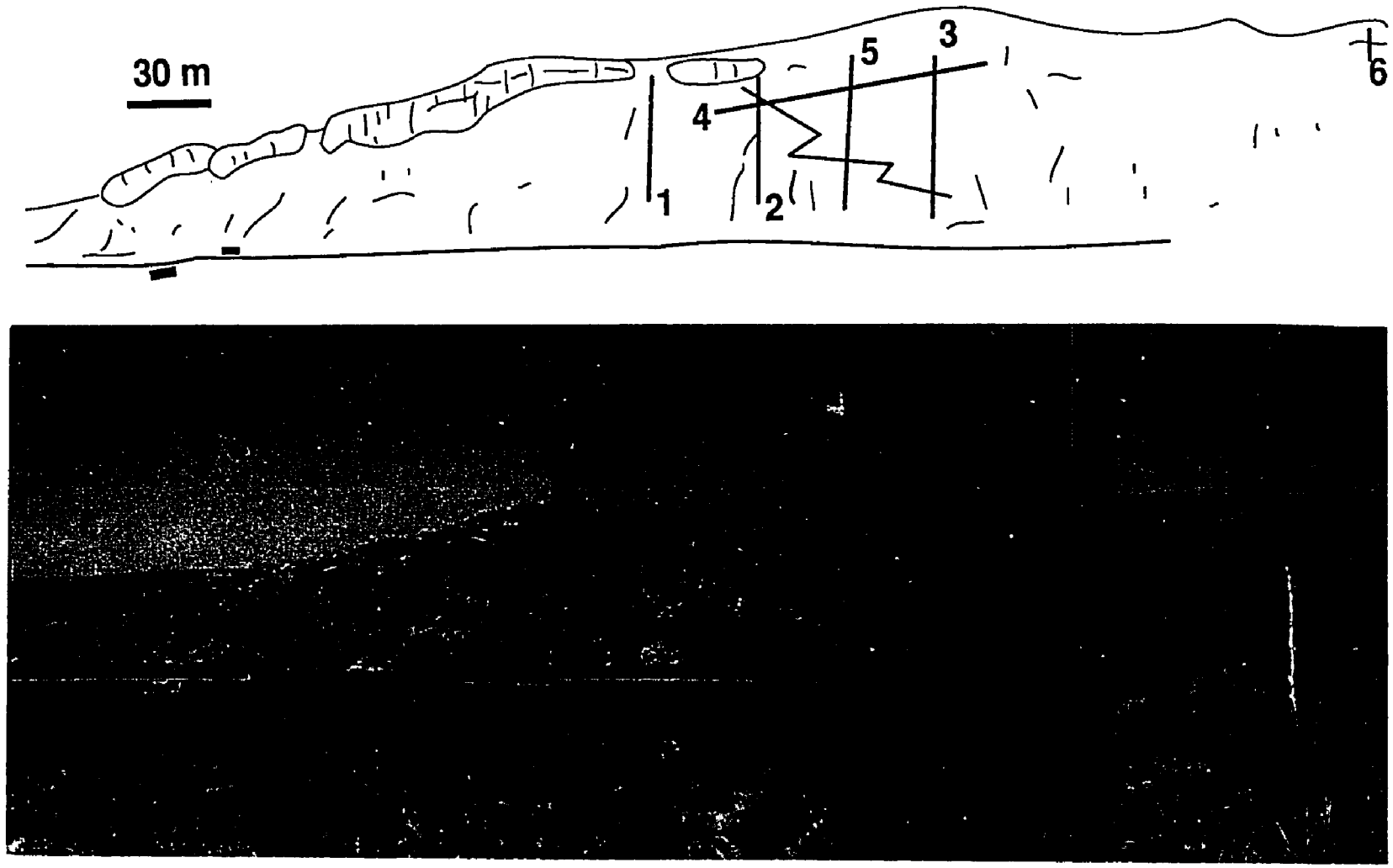


Figure 3.18. Photograph showing intensely studied area near the mouth of Walnut Canyon.

packstones of the shelf (Fig. 3.19). This transition may occur over as short a distance as 5 m.

The transition between the Capitan Formation (reef) and the Yates Formation (shelf) was studied in a measured section in Rattlesnake Canyon and along the reef trail in McKittrick Canyon (Fig. 3.5). Similar facies and similarly abrupt transitions were found in these areas.

The transition between the Capitan reef and the shelf deposits of the upper Seven Rivers Formation is gradational in Slaughter Canyon (Fig. 3.5). The transition between the Capitan reef and the shelf deposits of the lower Seven Rivers Formation is abrupt in North McKittrick Canyon (Hurley, 1987). Part of the Seven Rivers and lower Capitan transition has not been studied in detail, only maps and generalized measured sections are available (Hayes and Koogle, 1958). These outcrops are in regions of the Guadalupe Mountains that are accessible with relative difficulty, but that are potentially interesting for future study.

Comparison between the transition between the reef and shelf throughout the Capitan section suggests that the abrupt nature of the transition was generally consistent through time. The significance of this abrupt transition will be discussed in later sections of this report.

Facies types and distribution across the outer shelf

The facies types and their distribution on the outer shelf are significant to the interpretation of the Capitan Formation as a barrier reef. The facies types described and defined were based on study of closely

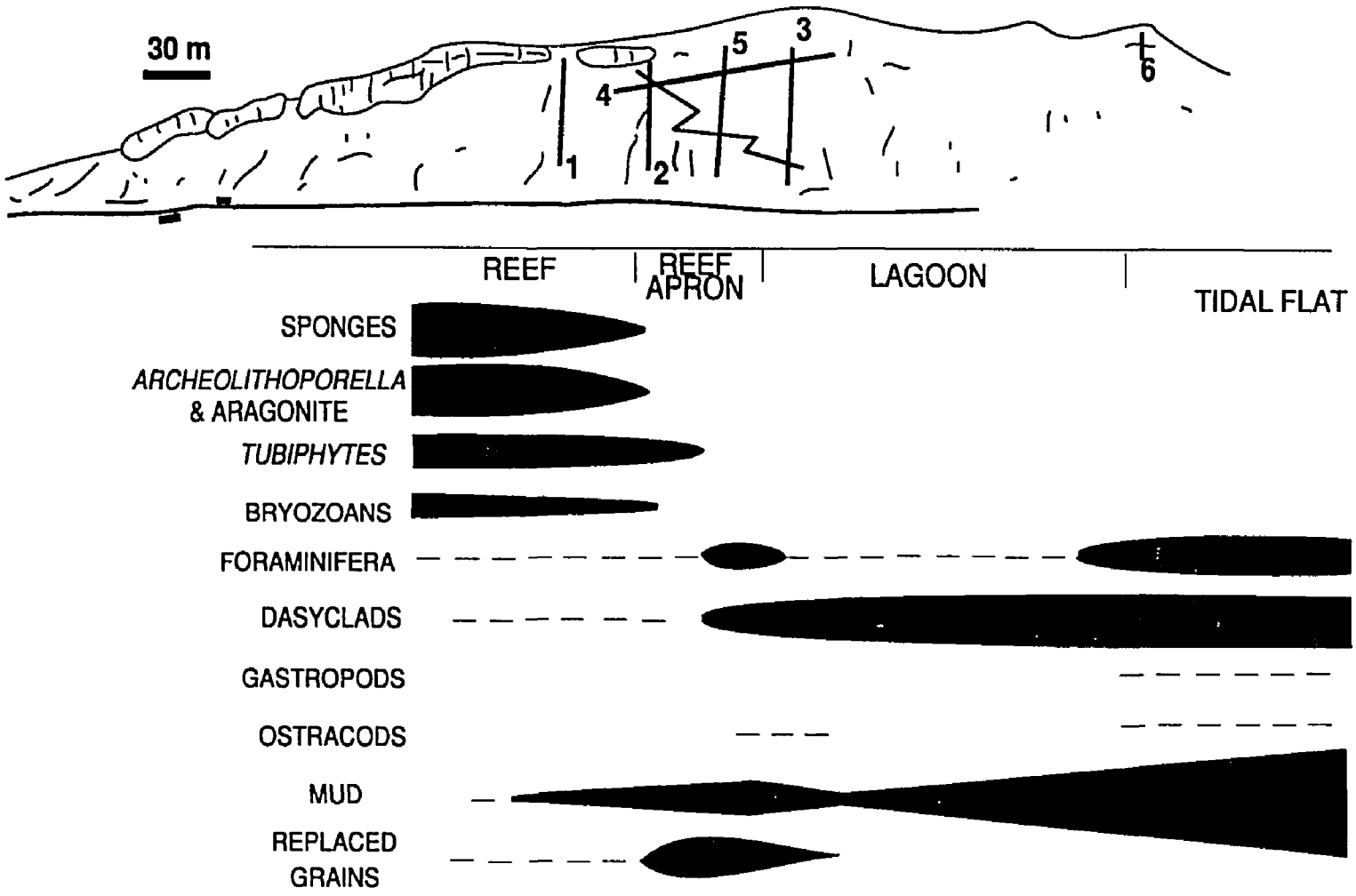


Figure 3.19. Sketch of area shown in Fig. 3.18 and relative amounts of significant fossils.

spaced samples from vertical and horizontal traverses and measured sections. Division of facies types was based on fossil types present and mud content. Final interpretation relied on sample location data, which had been marked precisely on photographs, maps and measured sections. Most of the facies defined here correspond closely, though not exactly, to the outer shelf facies defined by Neese and Schwartz (1977).

The facies type most commonly found shelfward of the reef is bioclastic grainstone and packstone (similar to the grain-supported skeletal-rich limestone of Neese and Schwartz (1977)). These rocks contain a variety of skeletal debris including: angular to subangular micrite-rimmed grains filled with sparry calcite, organically coated grains (probably algal or *Tubiphytes* encrustation), oolitically coated grains, dasycladacean algae, benthic foraminifera, trilobite fragments, fusulinids, and articulated brachiopods (not in growth position).

Bioclasts in these packstones and grainstones are thought to have been derived from the reef. This interpretation is based mainly on the high diversity of the fossils. In addition, the angular to subangular shape of many of the micrite-rimmed grains filled with sparry calcite is reminiscent of the shape of coral fragments found in sediment from a modern reef (Fig. 3.20). The shape of coral fragments is controlled by the spherical shape of the aragonitic particles that are stacked on top of each other to form the ultrastructure of the organism (Majewsky, 1969; Moore, 1989). Some calcareous sponges, both modern and ancient, have the same microstructure. Perhaps the angular- to subangular micrite-rimmed

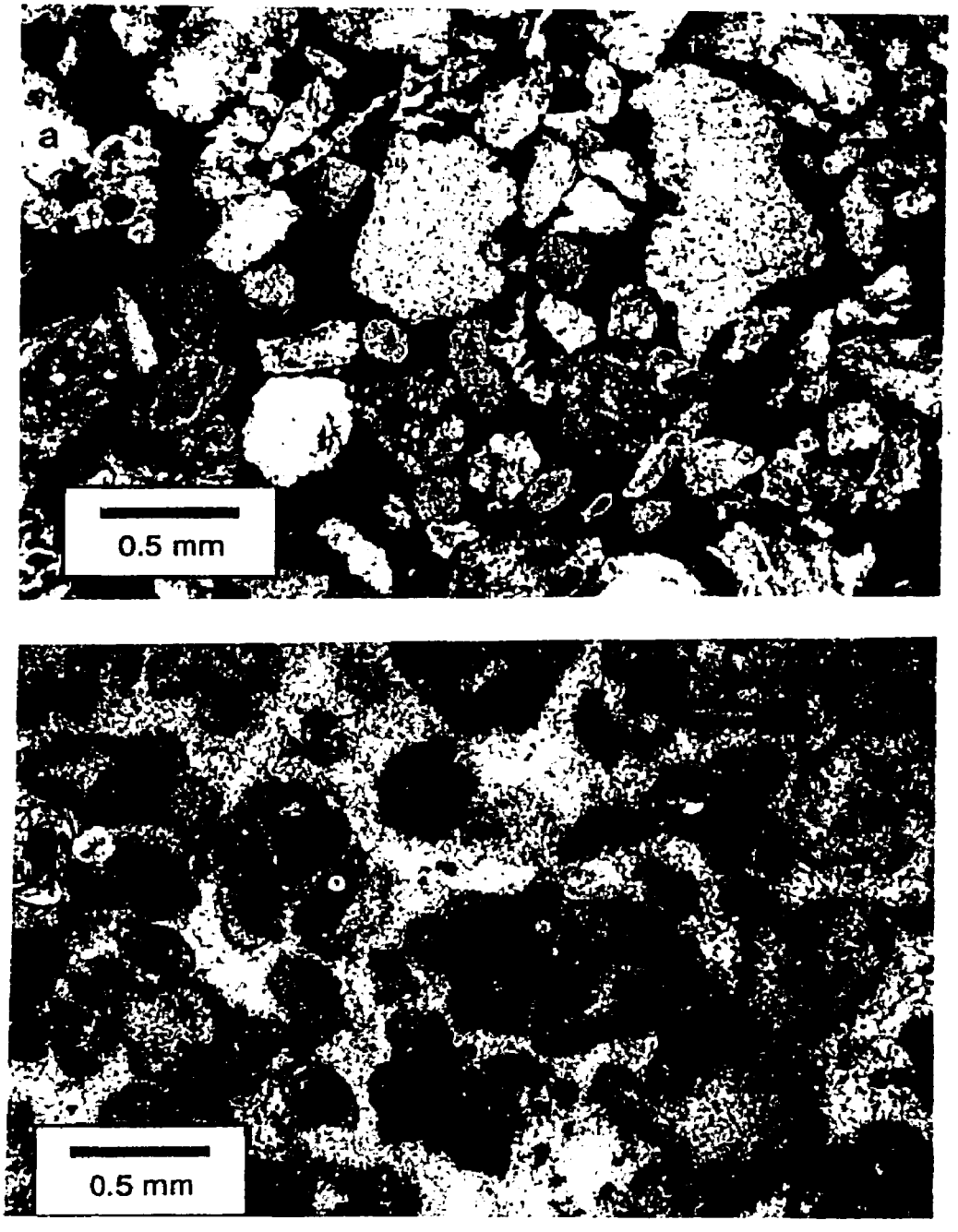


Figure 3.20. (a) Thin section photomicrograph of backreef debris collected at Tague Reef, St. Croix. (b) Thin section photomicrograph of Tansill Formation grainstone interpreted as Capitan reef debris.

grains filled with sparry calcite found in this facies are fragments of reef-dwelling aragonitic sponges.

Neese and Schwartz described the morphology of this facies as a "narrow belt 100-500 m wide, immediately shelfward of the Capitan Limestone" (sic) (Neese and Schwartz, 1977). They note further that this unit is composed of massive beds, 3-5 m thick. At the mouth of Dark Canyon and along the McKittrick Canyon Reef trail near the reef/back reef transition, oriented, articulated crinoid columnals (30 cm long) are present. These fossils were probably preserved in their articulated, oriented state because rapid accumulation of sediment, for example storm-related deposition, prevented disarticulation by currents or by burrowing organisms. This facies could be described as a sand shoal, but a more specific interpretation is possible. Based on facies morphology, location leeward of the reef, predominance of angular to subangular grain-shape, and abundance of reef-derived sediment, these bioclastic grainstones and packstones are thought to have been deposited as a back reef apron.

A second facies type is commonly found interbedded with the aforementioned bioclastic packstones and grainstones. This second facies type consists of dasyclad-dominated grainstones. Many samples are composed almost exclusively of round to barrel-shaped, hollow, 1 mm diameter segments of dasycladacean algae (Fig. 3.21). Most samples are dominated by the genus *Mizzia*, other samples are dominated by *Macroporella*. This facies was found only as beds in canyons and was not found along the escarpment.

Two interpretations of this facies are possible. The dasycladacean algae may have lived preferentially in high-energy environments, resulting in their deposition in dasyclad-dominated

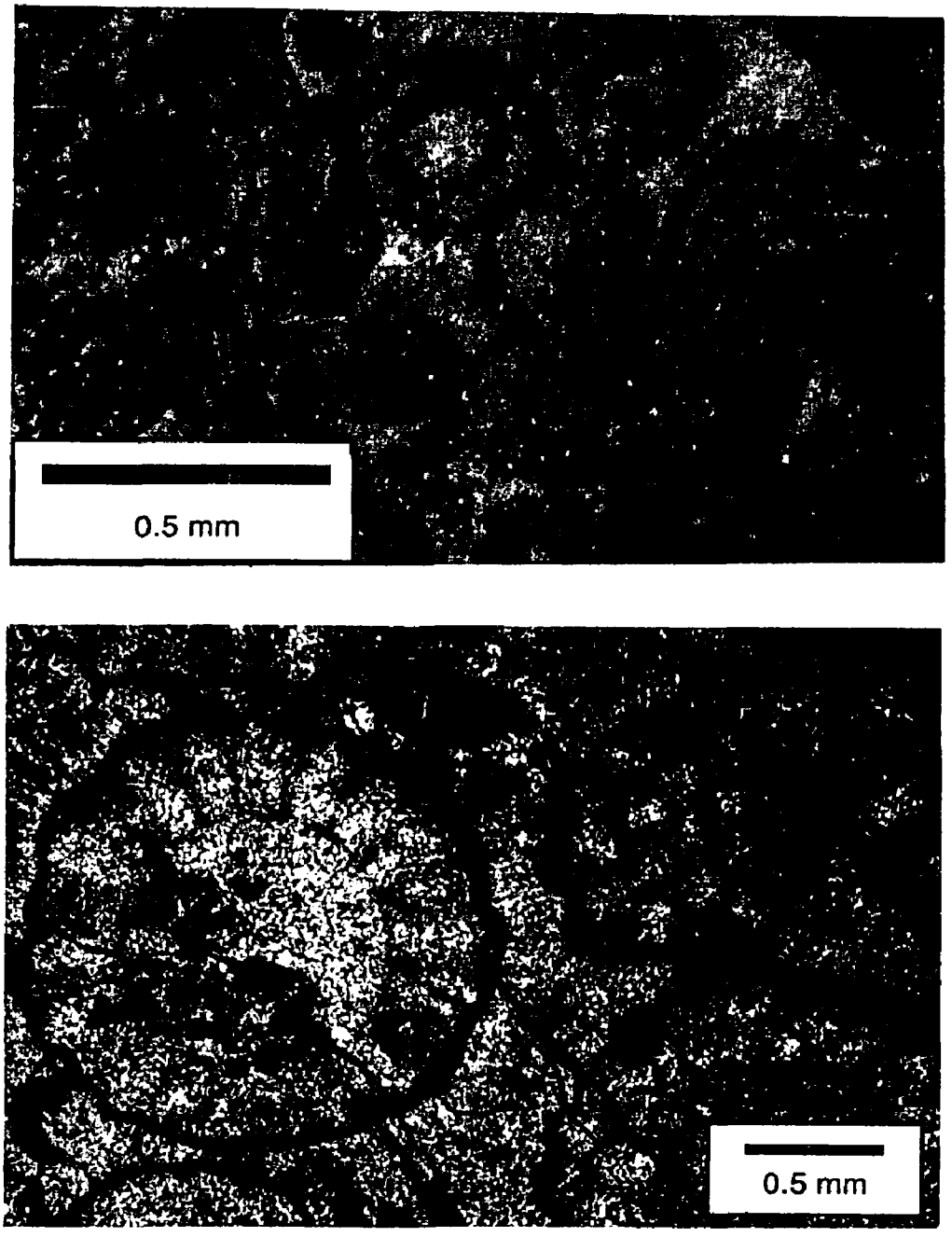


Figure 3.21. (a) Binocular photomicrograph of grainstone dominated by fragments of *Mizzia*, each approximately 1 mm in diameter; naturally weathered float. (b) Thin section photomicrograph of *Mizzia* segments from a *Mizzia*-dominated grainstone. Both samples are from the Tansill Formation in Walnut Canyon.

grainstones. This interpretation is not considered likely, however, because modern dasycladacean algae prefer low-energy environments. Alternatively, this facies probably represents accumulations of particles of low specific gravity and uniform size, analogous to clusters of fishnet-buoys on a beach. These *Mizzia* grainstones seem to be transported accumulations of *Mizzia* located within paleochannels between sections of the reef. Restriction of this facies to present day canyons further supports this hypothesis.

Near the reef, the outer shelf is dominated by grainstones and packstones, but further shelfward mud content increases and a third facies, peloid, foraminifera, dasyclad packstone and peloid packstone is present (grain-supported, skeletal, non-skeletal facies of Neese and Schwartz (1977)). These rocks, dominated by rounded, micritic peloids and irregularly shaped micritic grains, also contain dasyclads, foraminifera, ostracods, gastropods, and micrite-rimmed grains filled with sparry calcite (Fig. 3.22). This facies zone is approximately 400 m wide and is elongate parallel to the shelf margin. Content of micrite increases shelfward. High mud-content, and restricted biotic assemblage (dasyclads, gastropods, and ostracods) occur in beds shelfward of the area of pisoid-tepee development.

The dasycladacean algae and foraminifera that dominate this facies have been interpreted as being indicative of restricted, slightly hypersaline waters (Adams and Rhodes, 1960; Neese and Schwartz, 1977; Esteban and Pray, 1983). Modern dasycladacean algae are known for their tendency to proliferate in warm, shallow hypersaline conditions (Beadle, 1988). In addition, preservation of

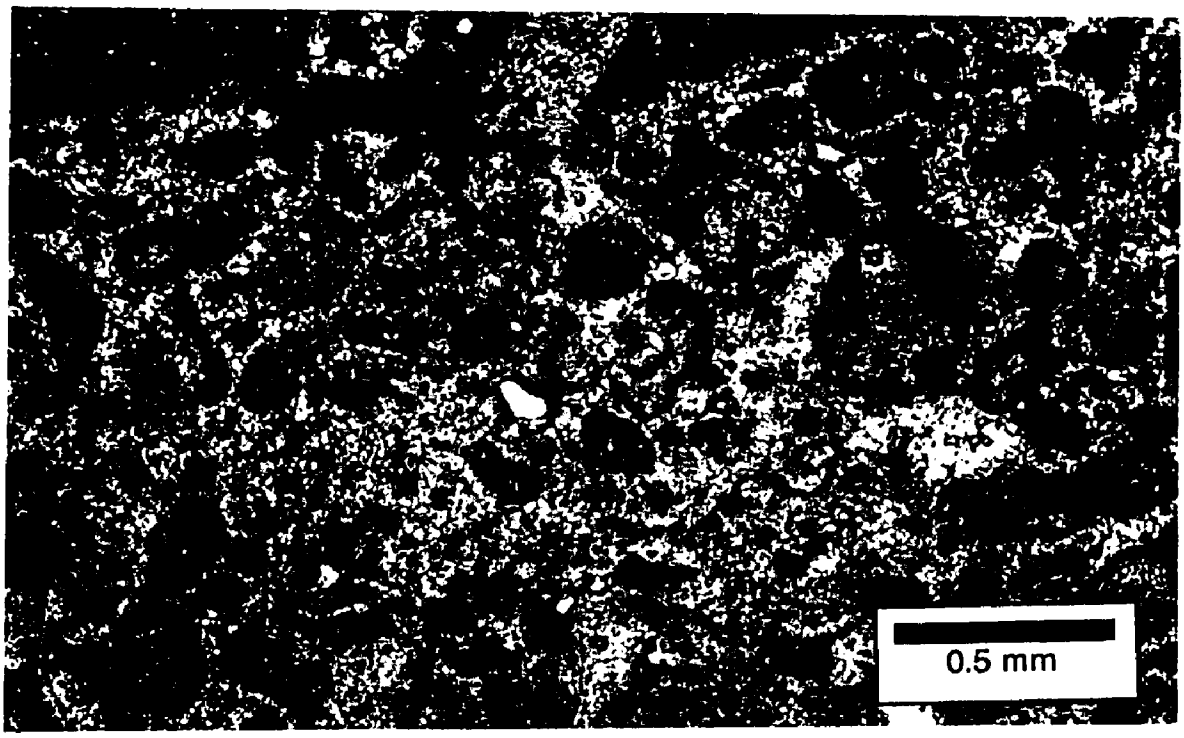


Figure 3.22. Thin section photomicrograph of peloid packstone from the Yates Formation in Rattlesnake Canyon.

articulated sections of dasyclad thalli suggests low-energy conditions (Kirkland and Chapman, 1990). Further interpretations can be made based on the large number of completely micritized grains in samples of this facies. Where biological activity exceeds the effect of current activity, biodegradation results in increased micritization of particles. A high percentage of micritized grains is typical of lagoonal sediment (Parsons, 1989). The increased micrite content in this facies provides further evidence of low-energy conditions. Based on biotic assemblage, high degree of micritization, and increased micrite content this facies is thought to have been deposited in a low-energy, lagoonal environment.

A fourth, volumetrically small facies is also found in this portion of the outer shelf. This facies consists of rounded peloid grainstones and packstones. Some examples contain possible keystone vugs. These samples may have been deposited as local shoals or possibly as local beaches along the shelfward margin of the lagoon.

Samples of the peloid, dasyclad, foraminifera packstone and peloid packstone facies are interbedded with, and transitional to, a fifth facies: packstone and wackestone containing micrite-rich pisoids (the grain-supported, pisolith-poor dolomite of Neese and Schwartz (1977)). The micrite-rich pisoids have indistinct laminae and their nucleus may be sharp, obscure, or indistinguishable. The term micrite-rich pisoids encompasses a range of particles, probably of varying, indeterminable origins. Some of the micrite-rich pisoids are certainly oncoids (Esteban and Pray, 1983). Other grain types present include: peloids, intraclasts, ostracods, foraminifera,

dasycladacean algae, and possible calcispheres. Algal laminae and small (1-3 cm) stromatolitic heads are present in some samples (Fig. 3.23). Silt to very fine sand-sized siliciclastic material is scattered through some samples. The matrix of all the samples is micrite or sporadically micrite with a clotted texture. Fenestral fabrics are also present in some samples of this facies (Neese and Schwartz, 1977) (Fig 3.24). One sample contains molds that suggest removal of lath-shaped evaporite crystals (Fig. 3.25).

The fossils present suggest that micrite-rich pisoid packstone wackestone facies was deposited in hypersaline waters (Neese and Schwartz, 1977). Fenestral fabrics suggest deposition in a supratidal environment, although they can be formed in, and preserved from, upper intertidal environments as well. Preservation of fenestral fabrics is dependent on early lithification (Shinn, 1983). This facies is interpreted as having been deposited along the shelfward margin of the outer shelf lagoon in an area transitional to low-energy tidal flats. The presence of evaporite molds suggests that at least locally conditions may have been hypersaline. Tidal flat facies were not defined by Neese and Schwartz, but they were recognized from the outer shelf portion of the Tansill Formation by Parsley (1988) and Rudolph (1978). The final outer shelf facies to be considered in this discussion is pisoid grainstone and packstone (the grain-supported, pisolith-rich dolomite of Neese and Schwartz, 1977) (Fig. 3.26). These grainstones and packstones are almost always associated with tepee structures (Neese and Schwartz, 1977; Esteban and Pray, 1983) (Fig. 3.27). Because the dominant particles in this facies, pisoids,

Figure 3.23. Slab photograph of stromatolite sample from tidal flat facies. Collected in Walnut Canyon.

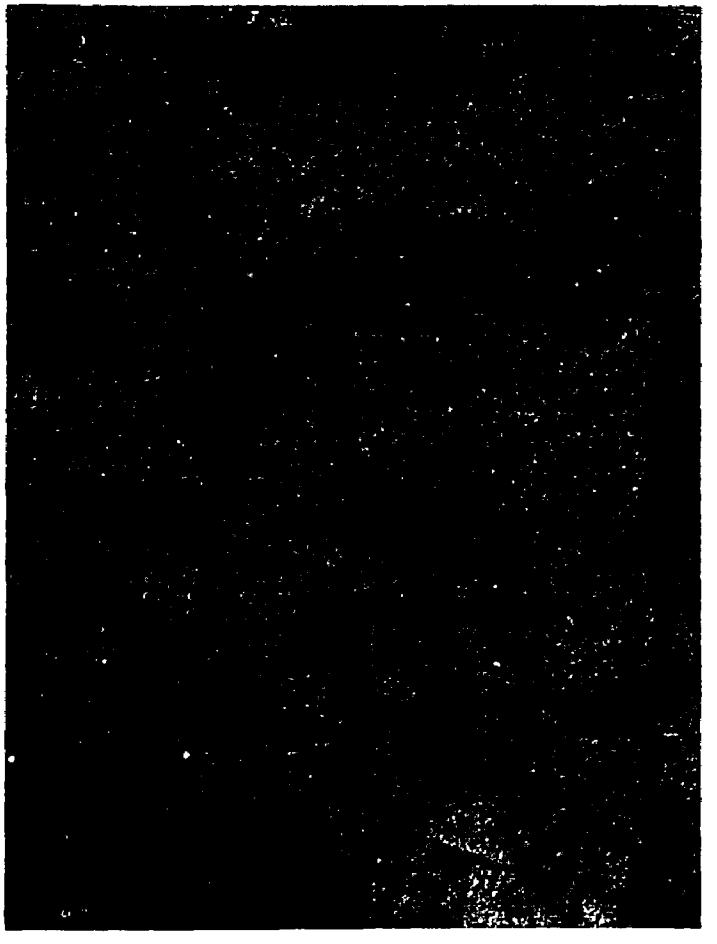


Figure 3.24. Fenestral fabric in outcrop near Rattlesnake Canyon.

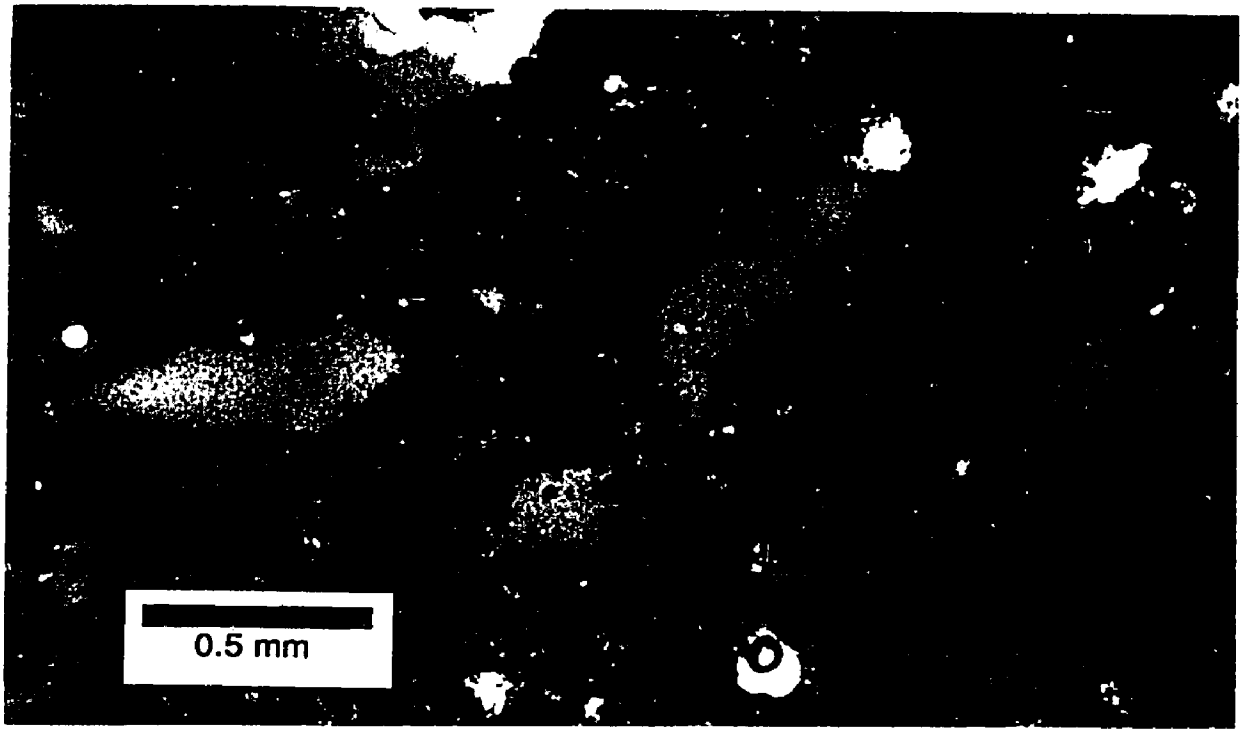
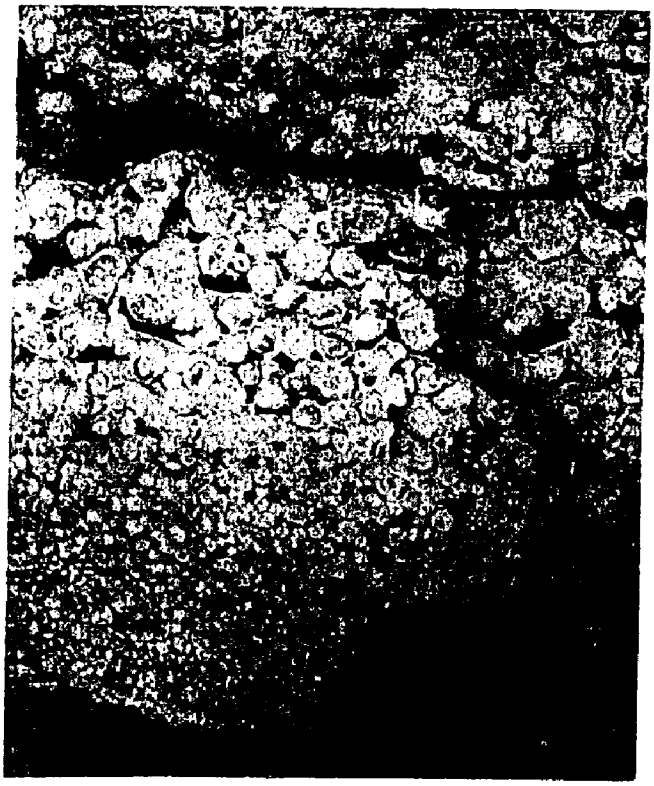


Figure 3.25. Thin section photomicrograph showing evaporite (gypsum?) molds.



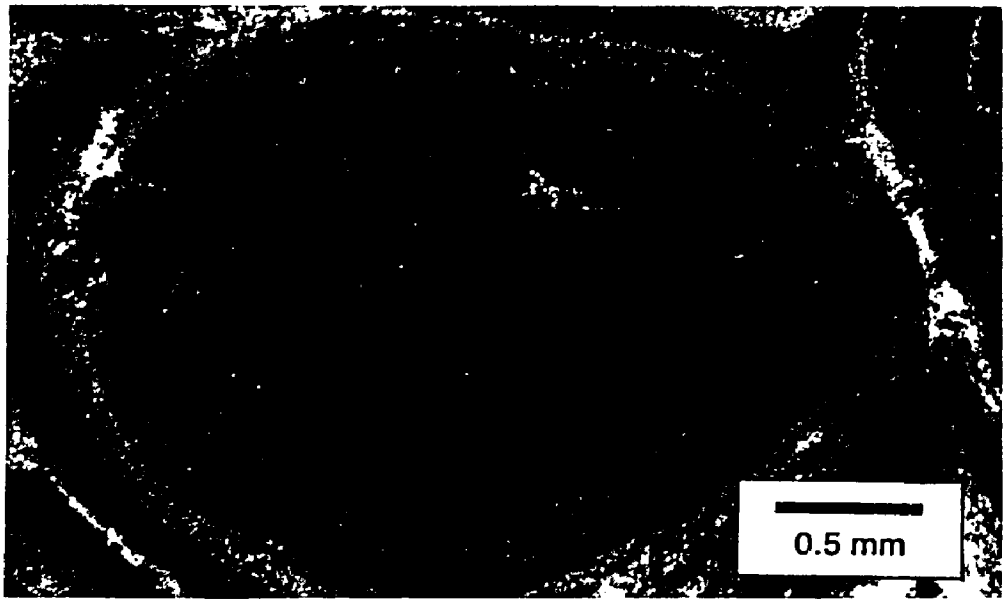


Figure 3.26. (a) Pisoids in outcrop showing inverse grading. (b) Thin section photomicrograph showing concentric isopachous laminae and broken pisoid nucleus.

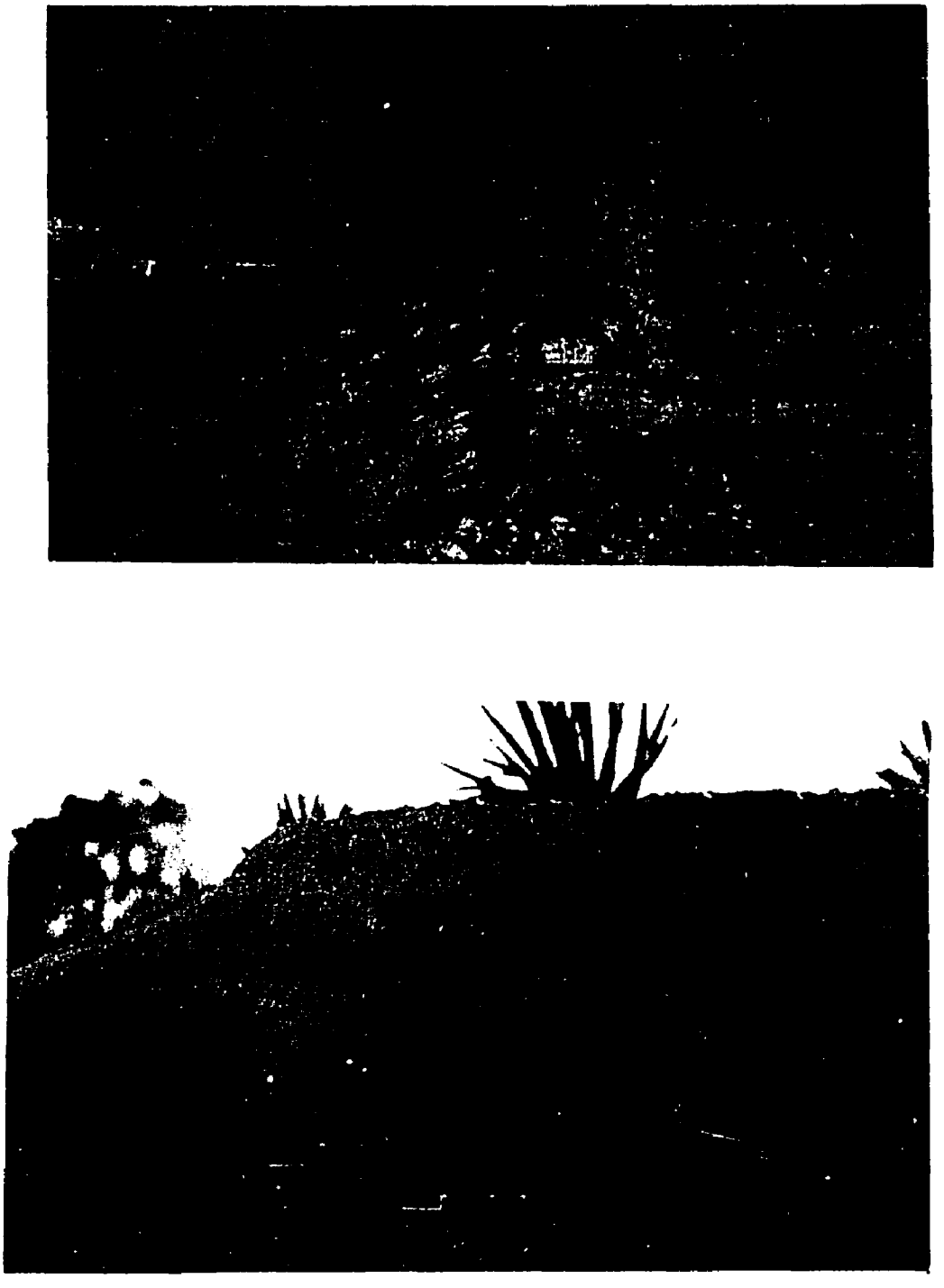


Figure 3.27. (a) Tepee structure in Dark Canyon. (b) Pisoids associated with tepee structures in Walnut Canyon.

have already been described in detail (Esteban and Pray, 1983) only a few relevant features will be discussed here. Inverse grading is present in some pisoid beds (Fig. 3.26a). These particles are probably the result of inorganic precipitation. They consist of many small, accretionary isopachous laminae (Esteban and Pray, 1983). The laminae are smooth and evenly spaced and do not resemble the clotted, irregular laminae of algal nodules. Broken pisoids often form the nucleus for other pisoids (Fig. 3.26b). All samples examined for this study were completely dolomitized. Etching followed by examination with SEM revealed no evidence of bacteria in association with the laminae, but microbial fossils, if they had been present, could easily have been destroyed by dolomitization. In addition, stratigraphic cross sections suggest that pisoid deposition was cyclic, alternating with peloid packstone and grainstone (Neese and Schwartz, 1977; Hurley, 1989). Pisoid sequences were 3-8 m thick (estimated from cross sections) (Neese and Schwartz, 1977; Hurley, 1989).

Two significant interpretations can be derived from the information about pisoids presented here. First, the evenly spaced, smooth, concentric laminae suggest that the pisoids are probably the result of inorganic precipitation. Second, the abundance of broken grains suggests rapid precipitation from hypersaline waters (Sandberg, 1975; Esteban and Pray, 1983).

Outer shelf facies—interpretations

The strongest evidence suggesting that the Capitan reef acted as a barrier is the abrupt change from a high-diversity open marine assemblage

on the shelf margin to a low-diversity assemblage of salinity tolerant organisms on the outer shelf. In the arid Delaware basin climate, if the Capitan had acted as a barrier to circulation, then salinity could have increased in the back reef lagoon. This seems to be the case, as suggested by the presence of a biotic assemblage (gastropods, ostracods, and dasyclads) whose modern descendants are tolerant of extremes of salinity. Mud-dominated facies and the presence of stromatolites between suggest even lower energy, that on the shelfward margin of the backreef lagoon, more saline conditions developed.

The evidence for increased salinity on the outer shelf, the presence of a tidal flat island, and the abundance of inorganically precipitated pisoids, will be used in the next section to develop a model for the Capitan complex including a model for formation of pisoids.

DEPOSITIONAL MODEL FOR THE CAPITAN REEF COMPLEX

Shelf margin and shelf facies

The facies of the shelf margin and shelf are illustrated schematically in Figures 3.28 and 3.29. A framework reef formed along the Capitan shelf margin. It was populated by a diverse population of framebuilding sponges, binding algae, bryozoans, brachiopods, and many other organisms. Framework voids filled with internal sediment and prolific amounts of marine cement.

On the leeward side of the reef, reef-derived sediment piled up in a backreef apron. The reef apparently acted as a barrier to

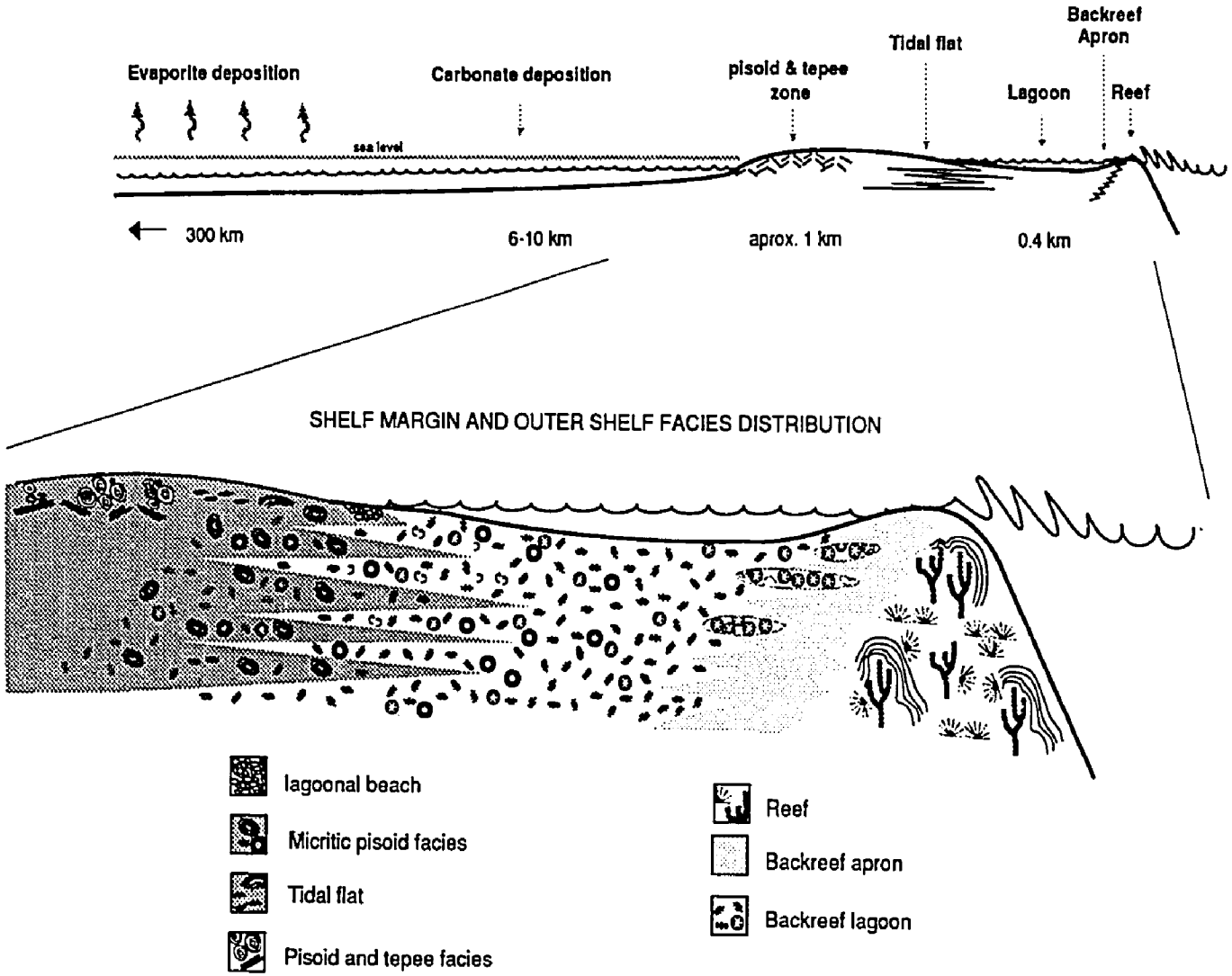


Figure 3.28. Schematic cross section of depositional model for Capitan Formation and outer shelf (below) and for entire Capitan complex (above).

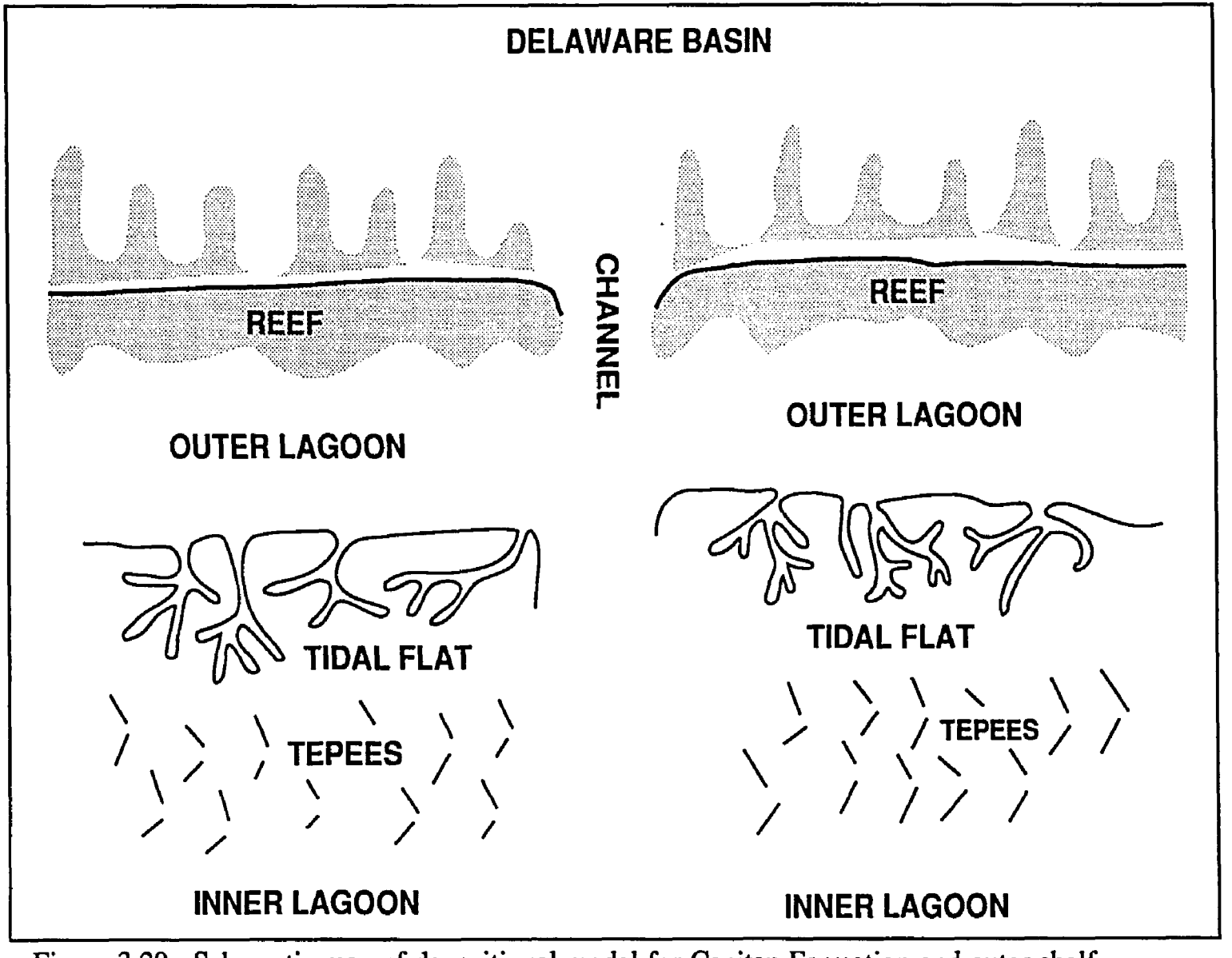


Figure 3.29. Schematic map of depositional model for Capitan Formation and outer shelf.

open marine circulation and controlled the type and distribution of facies deposited across the shelf. The backreef lagoon paralleled the reef and extended approximately 400 m shelfward of it. In sharp contrast to the reef, the backreef lagoon was populated by a low diversity assemblage of organisms that were all tolerant of hypersaline waters. No evidence of aragonitic marine cementation is found in the lagoonal facies. Localized accumulations of washed sediments were deposited as shoals or possibly as beaches and are interbedded with lagoonal facies.

On the shelfward margin of the lagoon (400 m from the reef), mud, probably winnowed from the lagoon and shelf margin, accumulated in a tidal flat. Micritic-pisoids and stromatolites may have formed in the intertidal zone. Abundant fenestral fabrics strongly suggest that a portion of this tidal flat was subaerially exposed. Shelfward of the tidal flat, in a zone approximately 1 km wide, pisoids and thick layers of cement formed in association with tepee structures. Shelfward of the zone of pisoid development carbonate deposition continued in a band 10-20 km wide (Sarg, 1981). Beyond this zone of carbonate deposition a huge evaporative lagoon extended for about 300 km. Gypsum, halite, and bitterns were precipitated in this lagoon and remnants are still preserved in the subsurface (Adams and Rhodes, 1960).

The Capitan reef seems to have acted as a barrier to open ocean circulation, allowing for development of a restricted biota in the back reef lagoon, and shelfward of that, formation of a mud-dominated tidal flat. The reef may also have been the primary control on a hydrologic system that allowed tepee springs and

associated pisoids to develop.

Two observations suggest that at least some of the Guadalupe Mountain pisoids formed in association with springs. In the upper Yates Formation in Dark Canyon, fractures within tepee structures contain sand and flame (?) structures suggesting upward fluid flow. In Walnut Canyon tepee structures crop out north of the hairpin-turn locality of Neese and Schwartz (1977). Some tepee structures involve approximately 15 m (50 ft) of section, and suggest that an on-going process controlled their formation. Parsley (1988) also suggested that some of the Guadalupe Mountains tepees might have been associated with springs. The abundance of fractured grains suggests that the waters from which the pisoids precipitated were probably hypersaline and supersaturated with respect to $CaCO_3$. Agitation associated with the springs may have triggered precipitation and may have resulted in formation of pisoids and cement bands.

Figure 3.28 diagrammatically illustrates a possible mechanism for formation of the hydrologic head. Continuous evaporation across the shelf resulted in an increase in salinity and a decrease in water volume across the shelf. This process caused the water surface in the evaporative lagoon to be lower than sea level. Water lost to evaporation and dense hypersaline water lost to seepage were replaced by water flowing down slope into the lagoon (Adams and Rhodes, 1960). The difference in elevation between sea level and the surface of the evaporative lagoon provided the hydrologic head to charge the tepee springs.

Modern tepee-mounds and associated pisoids and cements

found in Western Australia appear to be analogous to those of the Guadalupe Mountains. These tepee mounds are also associated with the formation of pisoids and cement bands. The Australian tepees form along the margin of Lake McLeod where water from the Indian Ocean seeps through a Tertiary barrier and discharges in active springs and associated seepage mounds (Handford et al., 1984).

DISCUSSION

The evidence presented strongly supports a sea level barrier reef depositional setting for the Capitan Formation. A single argument remains, however, that seems to support the marginal mound hypothesis. The most important observation is the "fall in bed" geometry of the outer shelf. In the lower Seven Rivers Formation in western North McKittrick Canyon, outer shelf beds dip 5-15°, becoming progressively steeper in the direction of the reef (Hurley, 1977; 1989). This observation is the basis for interpretation of the Capitan as a submerged shelf margin buildup, which is depicted in Figure 3.30a. The marginal mound model places the pisoid and tepee complex at the shelf crest; it places the peloid, foraminifera, dasycladacean algae packstone facies and the tidal flat facies on an open outer shelf that dips 5-15°; and places the reef in water well below wave base. The marginal mound interpretation seems to be based on the assumption that the present day erosional profile of the Guadalupe Mountains approximates an ancient time line.

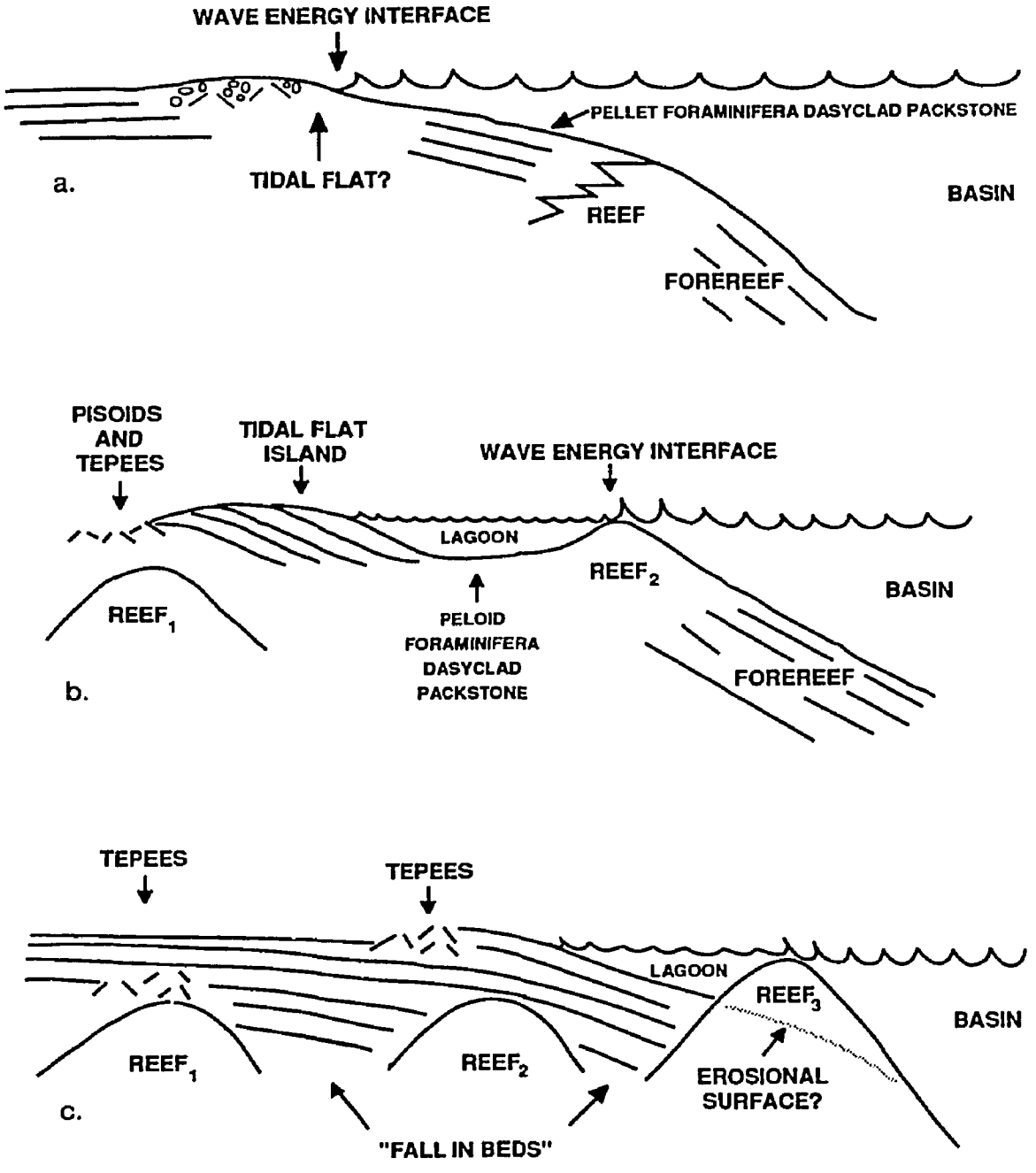


Figure 3.30. Schematic cross sections illustrating marginal mound model (a) and possible mechanisms for "fall in bed" formation (b and c).

We propose instead that the "fall in bed" geometry results from interplay between progradation and differential compaction of reef and lagoonal sediments. The reef facies, because of its rigid framework and abundant cement, compacts less than surrounding facies (Playford, 1980; Moore, 1989) Throughout its development Capitan reef growth had a distinct progradational component, although in the upper portion of the section aggradational growth dominates (King, 1948; Garber et al., 1989). Progradation of the Capitan reef is seen in Slaughter Canyon (Fig. 3.31). Analysis of this photograph suggests that actual progradation took place in discrete "jumps," with the establishment of reef shelf margins distinctly separated both laterally and vertically. This probably occurred in response to sea level perturbations.

Our hypothesis proposes that compaction-related antecedent topography developed from the shelf margin position of an old reef, controlled outer shelf hydrography and hence sediment distribution. The model is depicted in Figure 3.30b. The rigid, previous shelf margin would have remained as a high during compaction. A deeper lagoon would then have been formed between the previous shelf margin and the new reef. As in modern reef settings, the new reef would have grown up to sea level and would have stood in relief above the shallow lagoon floor. Mud from the reef and lagoon would have been transported shelfward by storm, and day to day processes, onto the old reef high. As in modern settings, storm deposits would have allowed this mud to be piled above normal high-tide level in a supratidal tidal flat, resulting in formation of a tidal flat island. As sediment continued to accumulate along the margin of the tidal flat island, the basinward, or reefward, side of the island would have

Figure 3.31. North wall of Slaughter Canyon. Capitan Formation stands in relief as massive rounded cliffs.

prograded towards the reef, onlapping the lagoon floor. This sediment would ultimately have filled in the lagoon behind the reef (Fig. 3.30c), resulting in the typical "fall in" structures characteristic of the rocks of the outer shelf. This model accounts for the abrupt transition between the reef framework and back reef sediment.

A modern analog for this scenario occurs in the area of Grand Cayman Island. An island behind the modern reef receives lagoonal and reef sediment resulting in distinct progradation of the island toward the reef, filling in the lagoon (Roberts, 1977).

The hypothesis for "fall in bed" formation proposed here presents a viable alternative to the marginal mound model. It accommodates all the facies described from the outer shelf, and it has a modern analog. It is, as all models are, an overly simplistic scenario for one point in time in the Capitan complex. Large portions of the section remain essentially unstudied. Initial inspection of the large, magnificently exposed outcrops deep in the Guadalupe Mountains reveal subtle lineations and onlapping relationships (Fig. 3.32). A true understanding of the "fall in beds" requires a through study combining integrated sequence stratigraphic and facies analysis.

CONCLUSIONS

Careful consideration of the data from a variety of sources leads to the inference that the Capitan Formation was deposited as a barrier reef and it is analogous to a modern reef in many ways. Like a modern reef, the Capitan reef was built by a diverse array of framebuilding and binding organisms. Voids within the reef filled with internal sediment and large

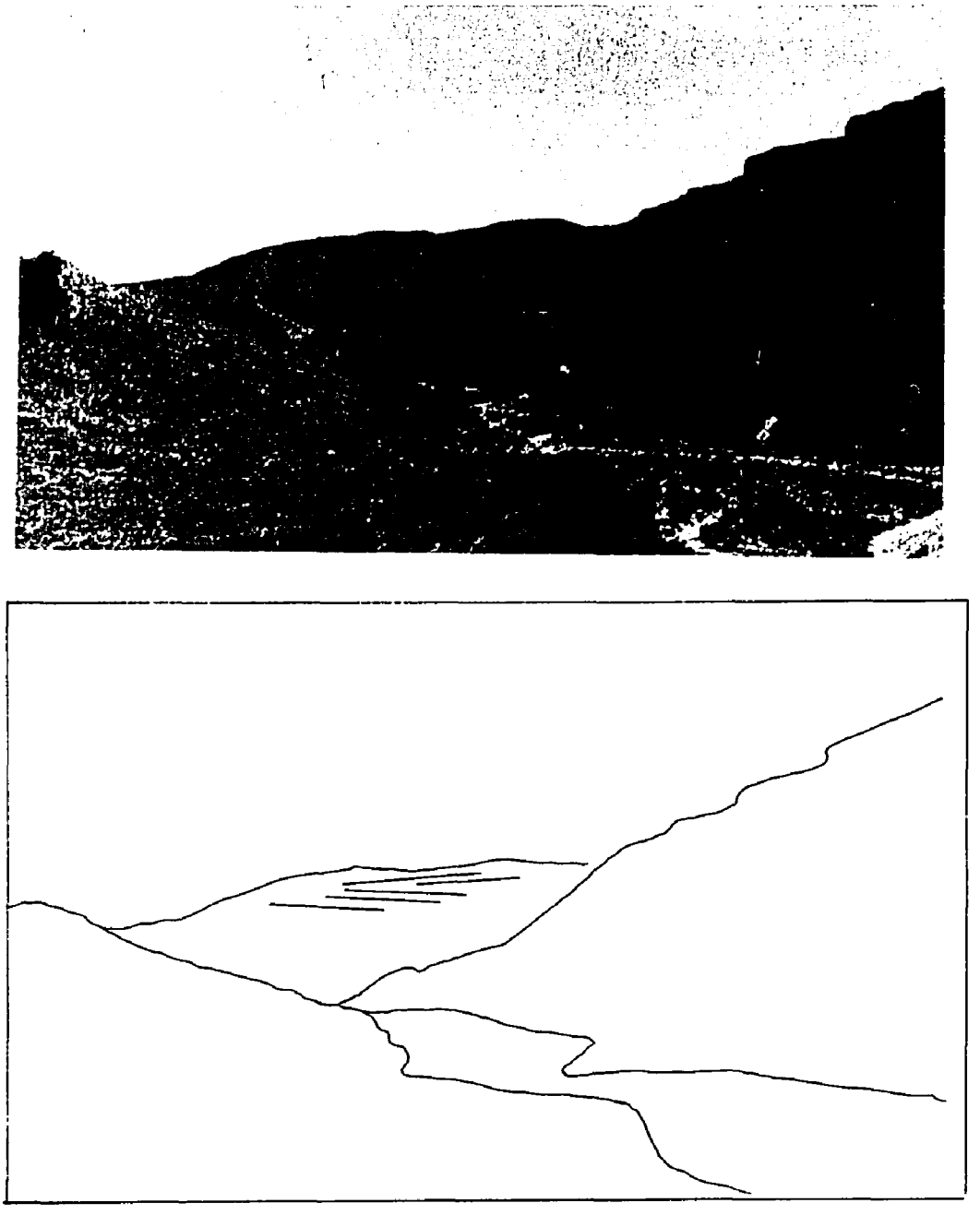


Figure 3.32. View facing west in Slaughter Canyon. Lineations in the hill in the center of the photo suggest onlap (approximately 1.6 km (1 mi) from photographer).

volumes of marine cement. The reef acted as a barrier to open ocean circulation, and the back reef lagoon became hypersaline. Salinity of the backreef lagoon is inferred from the hypersaline biota preserved there and from the progressive increase in mud shelfward. On the shelfward margin of the lagoon, muds were trapped in subaerially exposed tidal flats. Shelfward of the tidal flat island, pisoids were deposited in association with tepee springs. These springs were probably driven by the difference in elevation between sea level at the reef and the level of the surface of the inner-shelf lagoon, which was lowered by evaporation.

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CHAPTER V

CONCLUSIONS

The three studies presented here provide a practical, conceptual framework for the differentiation of reefs and bioherms. The first study establishes the analogy between modern *Halimeda* bioherms and ancient phylloid algal mounds. The second two studies provide strong stratigraphic, petrographic, and biological evidence that the Permian Capitan reef is a sea level barrier framework reef analogous to modern reef systems such as Belize. These studies do not propose to change the existing definitions. Instead they present a multifaceted approach to critical assessment of carbonate buildups.

The first study deals with the phylloid algae that dominate many bioherms in the Sacramento Mountains of New Mexico. Conclusions based on these remarkably well-preserved *Eugonophyllum* fossils substantiate proposed taxonomic affinities for the organism and, by linking *Eugonophyllum* to modern organisms, provide insight into the depositional mechanism for phylloid algal bioherms. The main conclusions of this paper are:

1) Preserved, aragonitic, internal, and cortical structures of *Eugonophyllum* are similar to those of modern udoteacean algae.

2) Reconstruction of the alga based on internal morphology and on published external reconstructions depicts an organism morphologically similar to modern *Udotea*.

3) The discovery of phylloid algae with well preserved, distinctly udoteacean internal structure suggests that Late Paleozoic phylloid algal mounds are analogous to modern *Halimeda* buildups.

4) Like modern *Halimeda* mounds, phylloid algal mounds probably formed in deep (50 m) water, and their growth might have been controlled

by the path of nutrient-rich currents.

The second paper concerns the green alga *Mizzia* from the Tansill Formation in the Guadalupe Mountains. The study defined the paleoecological setting of *Mizzia* by comparison to the morphologically similar dasycladacean alga *Cymopolia*. The main conclusions of the second study are:

1) *Mizzia* thrived in marine waters that were warm, at most moderately agitated, sometimes restricted, probably shallow, and probably hypersaline.
2) This interpretation, along with the location of the *Mizzia* fossils studied, suggests that the Capitan reef grew to sea level, blocked vigorous wave action, and formed a shallow, possibly hypersaline shelfward lagoon.
3) The suggested paleoecological setting for *Mizzia* is incompatible with the widely accepted marginal mound model, which predicts that the shelf margin reef existed below wave base.

The third study, is a detailed lithologic analysis of the Capitan Formation and the outer shelf portion of the associated Carlsbad Group in New Mexico and West Texas. This study suggests that the Capitan and associated formations were deposited as a barrier reef complex. The conclusions of this study are:

1) The Capitan reef was built by a diverse array of calcareous sponges that acted as framebuilders and calcareous algae that acted as binders.
2) Voids within the reef filled with laminated internal sediment similar to that in modern reefs.
3) Large volumes of aragonitic botryoidal marine cement filled voids in the reef, but not the back reef apron and lagoon.
4) The Capitan reef modified adjacent environments. This is suggested by the hypersaline biota in the back reef lagoon, and, on the shelfward margin

of the lagoon, the mud-dominated, subareally exposed tidal flats containing fenestral fabrics and algal structures.

5) Shelfward of the tidal flat island, pisoids were deposited in association with tepee springs. These springs were probably driven by the difference in hydrologic head between sea level at the reef and the level of the inner-shelf lagoon, which was lowered by evaporation.

Based on the information presented in these papers, application of the terms "reef" and "bioherm," as they were defined, require no new addendum to expand or refine the definitions. Instead they illustrate that the definitions already in the literature are completely adequate (Lowenstam, 1950; Dunham, 1970; Heckel, 1974). What these studies do provide, however, is an updated, multifaceted approach to application of the terms "reef" and "bioherm." Application of these terms represents more than just an exercise in semantics.

The distinction between reefs and bioherms is significant to exploration for and production of natural resources including: groundwater, hydrocarbons, and ores. The distinction between these two types of buildups is potentially useful for definition of porosity trends.

Framework barrier reefs tend to form along shelf margins, in waters that are agitated, well lit, warm, high in dissolved CO_2, and contain moderate levels of specific nutrients. They create an asymmetrical system where deposition is controlled by the reef. Brecciated forereef deposits form basinward of the reef, and shelfward, bedded sediments form in facies tracts that are elongate parallel to the reef. Marine cementation is most prolific in the reef, but it is also a significant, though less dramatic, process on the shelf. Zones of high porosity parallel the reef, and porosity is generally greatest in backreef sand and tidal flat sequence.

Algal bioherms, both ancient and modern, may be localized or part of a large system. They probably form in association with water that is rich in nutrients, and may form at depths ranging from (10-50 m). They may form at platform margins, as isolated pinnacles, and in association with reefs. They seem to exert little or no control on deposition of associated sediments. Porosity may be restricted to the mound, and is probably greatest within the build up or in associated flank beds.

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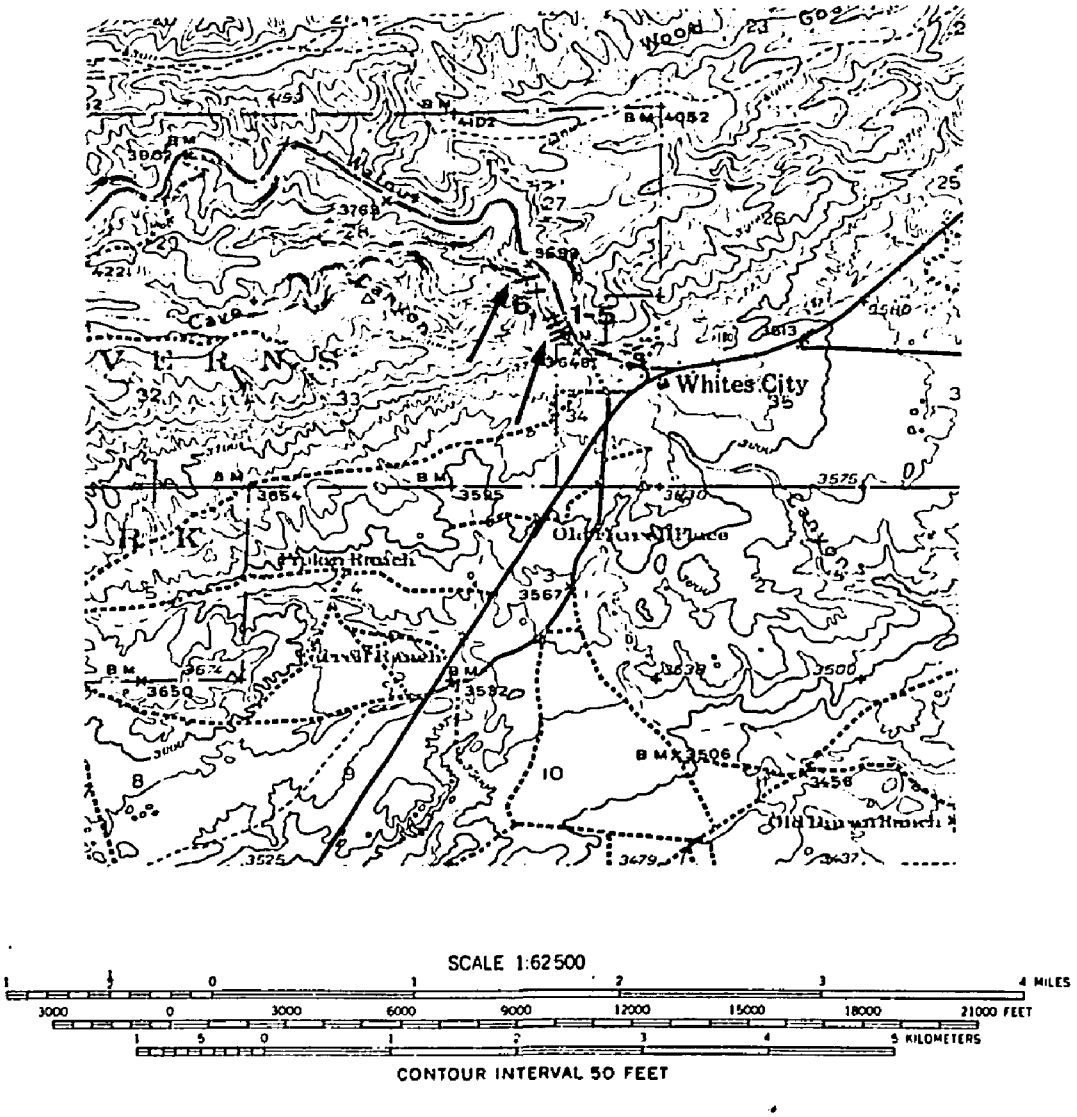
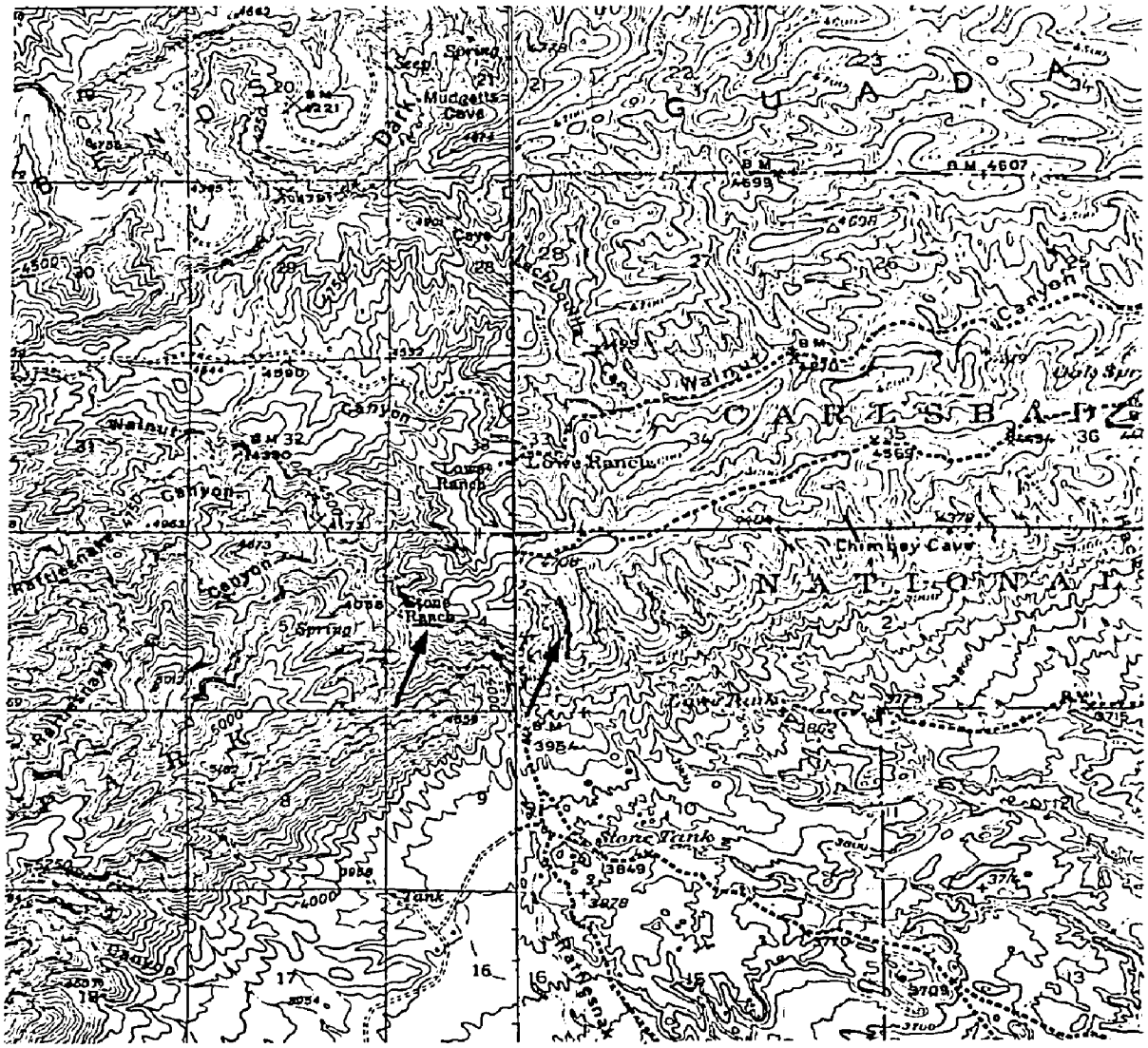
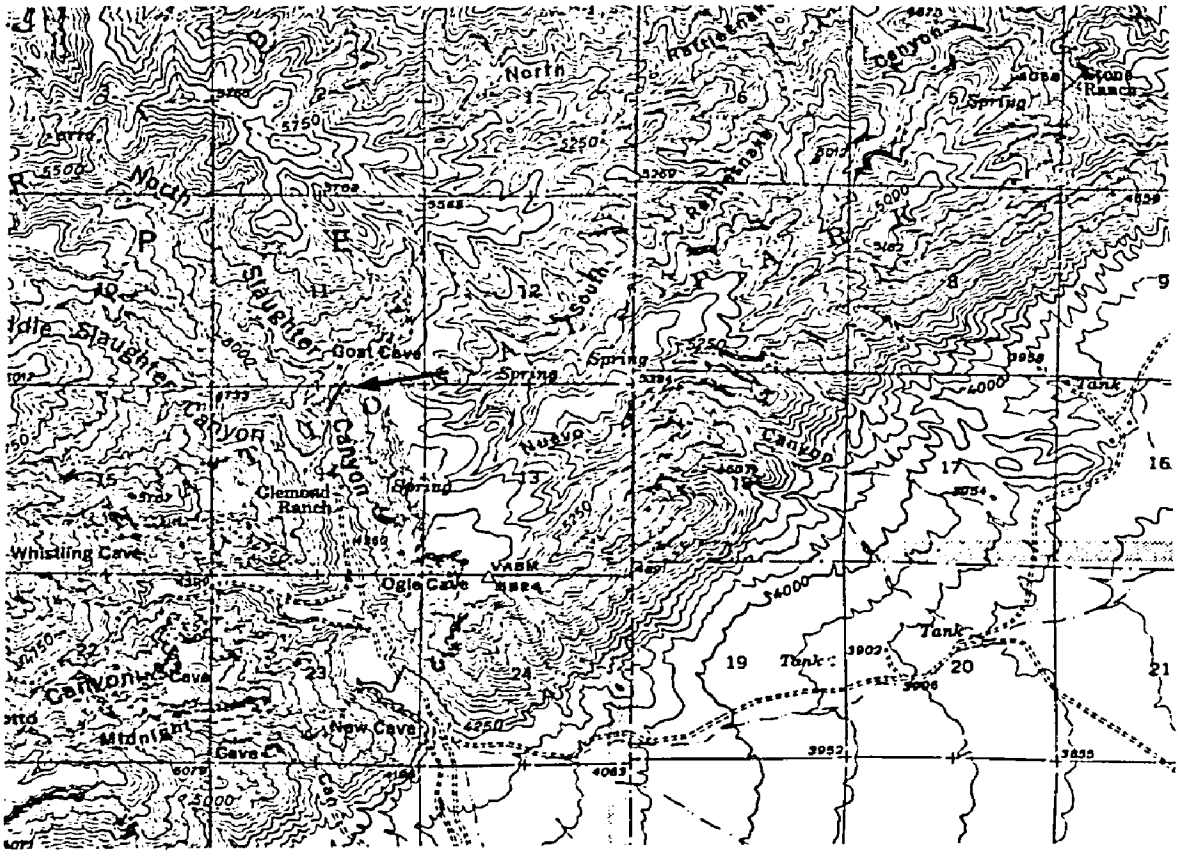
APPENDIX



1. Locations of traverses in Walnut Canyon. Scale applies to this map and to the following two maps.



2. Locations of measured section and traverse in and near Rattlesnake Canyon.



3. Location of measured section in Slaughter Canyon.

VITA

I was born in Durango, Colorado, but lived there only one year before moving to Albuquerque, New Mexico. In 1964, my family moved to Dallas, Texas, where my parents both worked as research geologists. My mother retired in 1991, but my father continues to work for Mobil's Dallas Research Laboratory.

I attended Skyline High School in Dallas. In the spring of 1977, I entered the University of Texas at Arlington, and spent the summer of 1977 in northern Germany. I entered the University of Texas at Austin that Fall, and completed a B.A. in German in December of 1980 and a B.S. in geology with a minor in botany in August of 1982.

I spent the scholastic year 1982-83 studying geology at the Ludwig-Maximillians Universität in Munich, West Germany. I began graduate study in geology at Texas A&M University in January of 1984. In the summer of 1986, I completed my thesis on shelf-margin facies of the Lower Cretaceous Sligo Formation under supervision of Dr. Thomas Tieh and Dr. Richard Rezak. In the fall of 1986 I began working at Louisiana State University under the the direction of Dr. Clyde Moore.

I worked for Mobil Exploration and Producing Services, Inc. in Dallas during the summers of 1984 and 1985; and in New Orleans in the summer of 1987.

In 1990 I was married to Peter Gillham George. My husband, also a Ph.D. candidate at Louisiana State University, is studying structural geology and fission track geochronology.

Present address: Department of Geological Sciences, P.O. Box 7909, University of Texas at Austin, Austin, Texas 78713-7909

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Brenda Kirkland George

Major Field: Geology

Title of Dissertation: Distinctions Between Reefs and Bioherms Based on Studies of Fossil Algae: MIZZIA, Permian Capitan Reef Complex (Guadalupe Mountains, Texas and New Mexico) and EUGONOPHYLLUM, Pennsylvanian Holder Formation (Sacramento Mountains, New Mexico)

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

November 25, 1991